SCIENTIFIC INSTRUMENTS II

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II

Edited by

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PREFACE

The success of *Scientific Instruments* first published in 1946 and since reprinted and also favoured by an American edition made a second volume inevitable. This second volume is similar to the first although there is no duplication between the two and whereas the present volume does to some extent elaborate some of the subjects mentioned in the first, it is in the main devoted to entirely new subjects. This volume will partially, but not completely, meet the criticism occasionally raised against the first that certain instruments were omitted. Of course they were—and still are. An attempt to cover all scientific instruments would either have been a mere catalogue, or if the treatment was at all useful, would have meant a library and not a book.

The Editor and the Publishers are quite well aware that there are still very many instruments requiring treatment on the lines given in these books, and if the reception accorded to this volume is anything like that given to the first, another may follow in due course. As a matter of fact such a volume could almost be written about instruments that have been omitted after careful deliberation from the first and second volumes alone.

The object of the book, however, is still, as was stated in the preface to the first volume, to be valuable to the general student and to the research worker, as well as to the many people who are using scientific instruments. It is not intended to be an exhaustive treatise on the functioning and design of the instruments described. Precedence has been given throughout to principles rather than to practice, the latter inevitably being a matter primarily for a book on individual instruments. Each chapter is intended to appeal not to the specialist in the field that it covers, nor to the users of the particular instruments therein described, but rather to the specialist in other fields and users of other instruments who would like to know what instruments and implements are used by different workers.

With such a wide variety of subjects certain differences in the treatment have been inevitable, but it is hoped that the reasons for these differences will be apparent. A special word may, however, be said perhaps about Chapter XXIII on Strategical Computing Machines in which more conventional treatment on the lines of a technical description was quite impossible within the space limits.

Rather than omit a chapter that may give useful information to many enquirers it was felt that its rather specialised and unusual treatment might be justifiable.

The book has been made possible only by careful collaboration and particular thanks should be expressed to Mr. Home Dickson for his many valuable suggestions and unstinted help. Also to Mr. W. H. Johnson for his guidance through all the stages of the book including its inception.

A list of acknowledgments is given of the various manufacturers and other organisations who have helped in numerous ways, chiefly by the loaning of illustrations, and if any name has inadvertently been omitted or if any copyright has unwittingly been infringed, apologies are hereby offered and a rectification promised in any later edition.

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SECTION 1

OPTICAL INSTRUMENTS

CHAPTER I

LENSES

In the first chapter of *Scientific Instruments* a short general account was given of lenses and their properties. It is proposed to begin this second book with some account of the methods used in the development and testing of lenses which are, of course, a fundamental item in the construction of a vast number of scientific instruments of all kinds. Unfortunately a lens, no matter how carefully made, can never attain absolute perfection, its defects being due to aberrations which were described in the first chapter of the previous book. For this reason instruments used in the manufacture and testing of lenses attain a vital degree of importance and are made to a very high standard of accuracy so that defects that cannot be eliminated can in many cases at least be measured and allowed for. The whole business of lens design, manufacture and use is a matter of compromise between theory and practice ; the theory itself would suffer inherent limitations if carried far enough, but practical considerations enter into the matter in a very definite way long before the ultimate theory is reached.

The Gaussian theory of image formation, in which assumptions are made which restrict the pencils of light to a very narrow zone about the axis of the system, can only be used as a first approximation in the design of a system and gives no indication of the effect of aberration. If the mathematical approximations are carried a stage further towards accuracy there emerge, from the resulting series, five terms or sums, known as the Seidel sums which correspond to the five spherical aberrations, namely spherical aberration, coma, astigmatism, curvature and distortion. Any attempt to carry the mathematical discussion to a higher order of accuracy introduces a large number of additional terms which are too cumbersome and laborious for practical use, and defects caused by the colour and the wave nature of light are also present. In the design of instruments and lenses it is not usual to carry the purely geometrical discussion beyond the evaluation of the Seidel sums, and in many instances, experience enables designers to dispense even with this work and to proceed with their design by ray tracing.

Tracing of Rays

The general design of a lens system having been determined by Gaussian methods, and, if necessary, by the application of the Seidel formulae, rays are traced through the system and the resulting image

patches obtained. Ray tracing, in the preliminary stages, can be carried out graphically on greatly enlarged diagrams of the system but the final work is entirely mathematical.

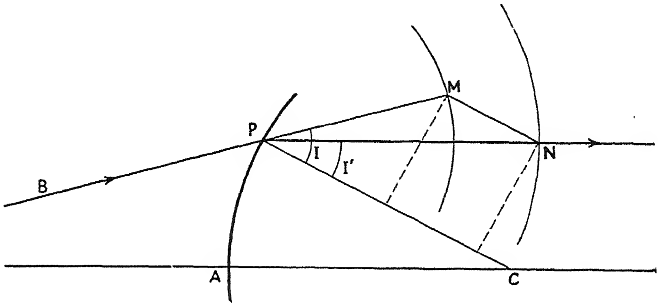

Fig. I. 1. Graphical ray tracing. AP is a spherical surface with centre C and P is the point of incidence of a ray BP. Two circles PM and PN are drawn, with P as centre, and radii proportional to the indices of refraction before and after the surface. MN is parallel to PC the normal at P then Sin MPC/Sin NPC=PN/PM= N'/N.

In graphical ray tracing the most convenient method to adopt is shown in Fig. I. 1. BP is a ray of light incident at P on the spherical surface AP whose centre of curvature is at C. With centre P and any convenient radius PM an arc of a circle is drawn cutting BP

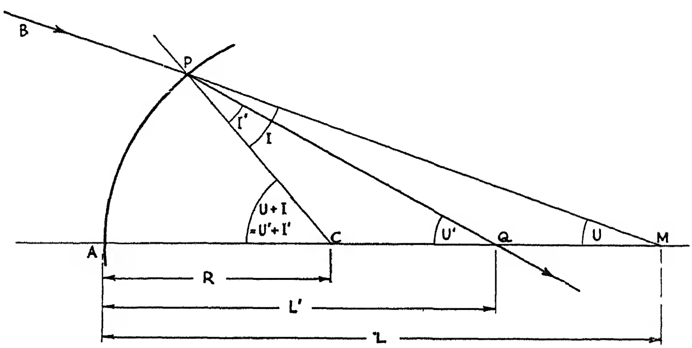

Fig. I. 2. Trigonometrical ray tracing. AP is a spherical surface with centre C and P is the point of incidence of a ray BP which is produced to cut the axis in M. PQ is the refracted ray and PC the normal.

$$(L - R)/\sin I = R/\sin U \qquad U + I = U' + I'$$

$$(L' - R)/\sin I' = R/\sin U' \qquad N \sin I = N' \sin I'$$

produced at M. Also with centre P and with a radius PN, such that PM is to PN in the same ratio as the refractive indices of the media before and after the surface, a second arc is drawn. MN is then drawn parallel to the normal CP at P and PN is the direction of the ray after refraction. The directions of the rays before and after refraction can be seen from the figure to obey the law of refraction since the radii of the two circles drawn about the point of incidence are proportional to the refractive indices (N and N′) of the media before and after the surface. Protractors to enable graphical ray tracing to be done are available and they use this same principle.

Mathematical ray tracing is most conveniently carried out by using trigonometrical formulae, but other methods are used, particularly where calculating machines are available. The trigonometrical method is based on the principle shown in Fig. I. 2 with the fundamental formulae, and the appropriate tables are available in relevant text books (see Bibliography at end of chapter).

Optical Glass

The range of optical glass available is fairly large and varied and a representative selection is described in *Scientific Instruments*, p. 11, with a short description of the manufacture. Optical manufacturers are informed by the glass manufacturer of any deviations from the catalogue values of the optical constants, but most manufacturers make their own measurements (a variation in the fourth decimal place of the refractive index may be of much importance).

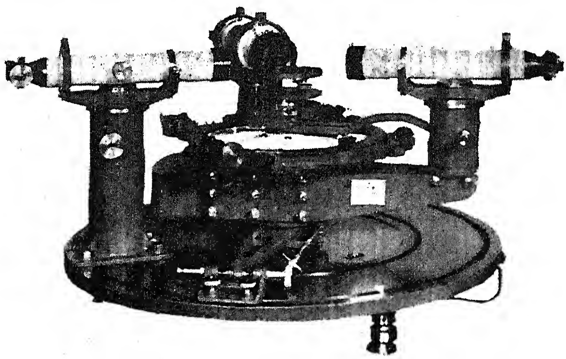

Fig. I. 3. Precision spectrometer (N.P.L. type).

Measurement of Refractive Index

The spectrometer is the fundamental instrument used for the measurement of refractive index. The measurements obtained with the spectrometer are absolute measurements of angles, and the

accuracy of the instrument depends primarily on the divided circle. Great care is necessary in the manufacture, adjustment and use of the spectrometer and the reader is referred to *Scientific Instruments*, Chapter VII, and to well-known text books for a full description and to the *Dictionary of Applied Physics*, Vol. IV, p. 760. To summarise, the instrument should be provided with two or four micrometers for reading the divided circle and the collimator and telescopes should be capable of adjustment for level and focus. Fig. I. 3 shows a Precision Spectrometer manufactured by Messrs. E. R. Watts & Son (London), for the National Physical Laboratory. One telescope is the main telescope of the instrument and the second an auxiliary which is used for focusing and levelling. The graduated circle of the instrument should be capable of independent rotation so that any part of the circle can be used.

The principal adjustments to the instrument consist in the focusing of the collimator and telescope both for parallel light of the wave length to be used for measurement, and the levelling of the collimator and telescope so that their axes are perpendicular to the axis of rotation of the instrument. Both these adjustments are made with the aid of the auxiliary telescope.

For the routine measurement of refractive index several well-known instruments are available, the Pulfrich refractometer being probably the most common. This instrument, like all other refractometers, requires calibration with standard glass specimens and a table of values is provided by the manufacturers from which the refractive index of any specimen can be found. The principle of the instrument is described in *Scientific Instruments*, Chapter VII. A recently designed refractometer which does not employ the critical angle principle of the Pulfrich is the Chance refractometer made by Messrs. Adam Hilger Ltd. (London). In this instrument the specimen is in

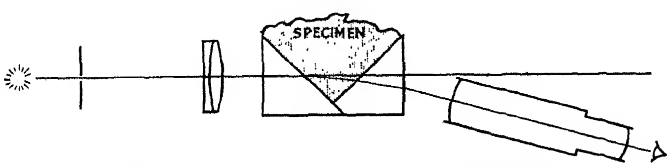

Fig. I. 4. Principle of Chance refractometer.

the form of a right angled prism which is inserted between two standard prisms so as to form a block with parallel faces as shown in Fig. I. 4. If the specimen has the same refractive index as the standard prisms the light suffers no deviation and if the index differs the deviation produced is a measure of the refractive index of the specimen and is capable of calibration. It is claimed for this instrument, which is illustrated in Fig. I. 5, that the specimen r[illegible] not be carefully polished or accurately right angled. A film ot liquid

of a suitable refractive index between the specimen and the standard prisms is used to eliminate the effects of lack of polish and inaccuracy of angle. The instrument is said to be capable of giving results of high accuracy comparable with that obtained by the use of goniometers.

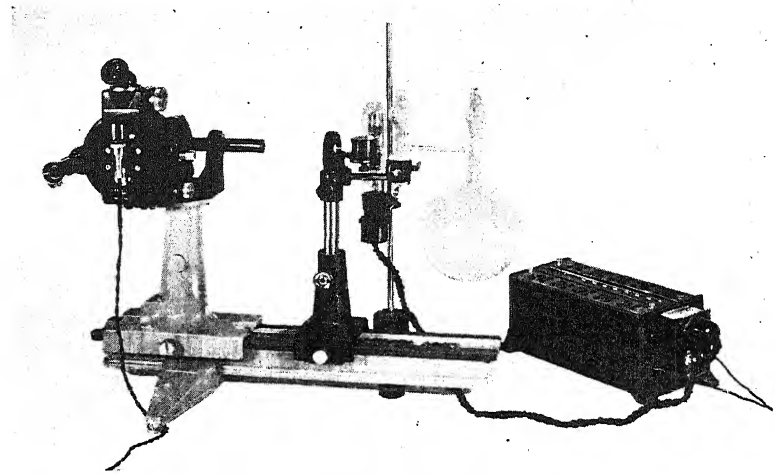

Fig. I. 5. Chance-Hilger refractometer.

Measurement of Radius of Curvature

The measurement of radius of curvature is of fundamental importance in the manufacture of lenses and the accuracy required, especially in routine measurement in the glass shops, is of an order never required in mechanical parts. Optical methods involving the use of test plates, or optical templates as they may be called, and the principles of interference of light are therefore used for all routine measurement. These test plates are pieces of glass or quartz which have been ground and polished with the greatest possible care and accuracy, to the required radius of curvature. The test plate is applied directly to the work and the interference fringes, known as Newton's rings, are observed, the number of fringes visible being a direct indication of the difference in curvature between the work and the test plate. The operator is instructed to continue his polishing of the work until a given number of rings of a uniform colour is obtained, the criterion being based on the accuracy of the work required. For the preparation of the test plates and the working tools and also, in special cases, for the measurement of actual components, measuring instruments, known as spherometers, are available.

The simplest form of spherometer consists of three rigid legs, terminating in points, attached to a stout plate through the centre of which passes a micrometer screw also terminating in a point.

The three fixed points are at the corners of an equilateral triangle and the centre micrometer point is equidistant from them. Although this instrument is capable of giving quite accurate results for medium curvatures and fairly large surfaces, its accuracy is not easily maintained and its use is too restricted for most optical work. In the Abbe form of spherometer the three fixed pointed legs are replaced by a ring which is not bevelled to a razor edge but is joined to an annular plateau so that concave surfaces make contact with the outer rim and convex surfaces with the inner. In place of the micrometer screw there is a central plunger which slides freely in guides and is pulled against the surface being measured by a definite constant force provided by a counter weight. The position of the plunger is measured by viewing in a microscope attached to the instrument a finely divided scale fitted to the plunger. An example of this type of spherometer is shown in Fig. I. 6.

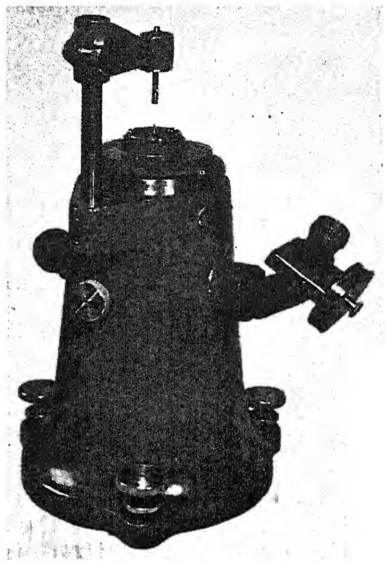

Fig. I. 6. Precision spherometer (modified Abbe type).

In the Aldis spherometer the surface being tested rests on three steel balls, a method of support which has much to recommend it, since the blunting difficulty is a minimum and there is less tendency to scratch the surface of the lens than in the other types. In the Aldis form the lens is held down on the balls by a weighted plunger and a central micrometer is raised from below the work until contact is obtained. The use of a sharp micrometer tip is open to objection and in the Guild form of the Aldis spherometer the sharp tip is replaced by a small quartz sphere. Contact is then found by using a vertical microscope to observe through the lens under test, the Newton's rings formed at the contact of the quartz sphere and the work. The instrument cannot be used for the measurement of opaque objects. For rapid work where the maximum accuracy is not essential a ring spherometer can be very easily made by mounting a dial gauge (see *Scientific Instruments*, p. 116) at the centre of a disc on which a ring is turned. A commercial form of dial instrument, called a dioptre-meter, is available for the testing of spectacle lenses.

In this simple instrument there are only two fixed and one movable points, disposed in a straight line, so that cylindrical surfaces can also be measured.

In addition to the instruments actually designed for the measurement of radius of curvature there are several methods of measurement available in special cases where the instruments become inaccurate or cannot be used. For very long convex radii the Newton's rings method is probably the most accurate and convenient and consists in placing the unknown curved surface in contact with a plane surface and measuring the diameters of the Newton's rings formed in monochromatic light, using some form of measuring microscope and vertical illumination with parallel light. For very long concave radii it is possible to find the exact position of the centre of curvature using the surface as a concave mirror to form an image coincident with and of equal size to the object, or by using the Foucault knife edge method. In the first method a convenient object can be in the form of a transparent fine scale, part of which is illuminated in such a way that its image is formed on the scale itself and observed by means of a microscope, the scale being adjusted in position until the image is coincident with the object and equal in size. In the Foucault test a point source of light is placed in position and adjusted so that the curved surface appears uniformly lit when seen through a pinhole situated by the side of the point source. If a knife edge is now slowly moved across the pinhole the surface of the mirror will grow dark uniformly if the source and pinhole are at the centre of curvature. This test is extremely sensitive and delicate and is used to test concave mirrors for astronomical telescopes.

For very short radii of curvature, microscopes fitted with internal illumination can be used in a variety of ways to locate the position of the centre of curvature.

Measurement of Aberrations

One of the commonest and most satisfactory methods of testing the performance of an optical instrument is to examine the image of a distant point of light both on the axis and in the outer parts of the field. An actual star could be used for the purpose but an artificial star, either in the form of a minute pinhole in a screen or, better, the reflection of a point source of light in a small sphere such as the bulb of a thermometer, set at a distance or at the focus of a collimating lens, is more frequently used. This star image method of test, in the hands of an expert, is very revealing and sensitive. The image should be examined with a high power eyepiece or a low power microscope, but the observer must ensure that the aperture of the eyepiece or microscope is such that all the light passing through the optical instrument enters the eye. For a detailed and full description of the test the reader is referred to H. Dennis Taylor's

excellent book on the testing of telescope objectives. By means of this star test it is possible to assess the correction for spherical aberration and chromatic aberration on the axis and any eccentricity or lack of symmetry in the system as well as the presence of strain caused by the mounting or inhomogeneity of the glass.

The Lens Testing Bench

Any normal optical bench can be used to test lenses and optical instruments but a special bench is usually more convenient for the purpose, in which the lens to be tested is mounted in a holder which allows it to be rotated about its optical axis. The holder is arranged to slide in a direction parallel to the lens axis, on a sliding member, which can be rotated about a vertical axis. In this way the lens can be made to swing about any point in its optical axis and it is usual to adjust the position of the lens until it swings about its second nodal point. The arrangement of slides is known as a "Nodal slide". The swinging portion of the nodal slide is fitted with a bar at right angles to the direction of the optical axis, and at an adjustable distance from the lens. This bar is known as the tangent bar and is used to maintain the viewing microscope or any other instrument or a photographic plate holder at the correct distance from the lens no matter how the lens may be rotated. Verniers, micrometers or dial gauges may be fitted to various portions of the slides and to the microscope or plate holder so that small movements can be measured and a circular scale fitted to the nodal slide indicates the angles of obliquity at which the lens is set. When the lens is adjusted in position so that it swings about its second nodal point the image remains stationary for small angular movements and it can then be examined at all parts of the field and, by moving the microscope along its own axis, at any position relative to the focal plane.

Chromatic Aberration

The source of light used in measuring the aberrations of lens systems is most conveniently provided by means of a monochromator. Many forms of monochromator are in existence and usually consist of a spectroscope of the constant deviation type (see *Scientific Instruments*, p. 83) arranged with a small aperture instead of a slit in the collimator, a constant deviation prism on a table fitted with a wave-length drum, and a second pinhole instead of the eyepiece in the telescope. By rotating the prism the pinhole in the telescope can be flooded with monochromatic light of any wave length. The pinhole of the monochromator should be placed at about twenty times the focal length of the lens from the lens. The image on the axis of the lens should then be examined in the eyepiece and its position noted.

By changing the colour of the light and measuring the movement in the position of the image the chromatic aberration can be plotted. It will be noted that no use has been made here of a collimator to form an image at infinity since, obviously, any errors in the collimator lens would be added to the errors of the lens under test. A collimator in the form of a concave mirror could however be used if considerations of space made it impossible to arrange the source at a considerable distance from the lens. The same source of light is used in measuring all the other aberrations and in this way the variations in the aberrations with wavelength are at once determined.

Spherical Aberration

The effect of spherical aberration on the position of the image can be simply estimated by measuring the movement of the eyepiece as different zones of the lens aperture are isolated by diaphragms. For actual measurement some variation of the Hartmann test is probably most suitable. A plate with a number of pairs of holes at measured distances from the lens axis is placed in front of the lens and the point where the pencils of light isolated by each pair cross is found, either by exposing photographic plates at positions inside and outside the focus and measuring the distances apart of the images, or by using a micrometer eyepiece to make the measurements. The test can be carried out for different wavelengths and the effect of colour on the spherical aberration thus found.

Coma

The effect of this aberration can be found by a variation of the Hartmann test, as explained above, for any oblique axis by arranging a suitable Hartmann plate in front of the lens which is set to the required angles of obliquity over the angular field, and measuring the positions of the pencils of light inside and outside the focus. This test is not very easy to carry out and the results do not help very much in the assessment of performance nor do they bear any simple relation to the usual method of assessing the aberration. It is therefore more usual to measure the focal length of the lens by some magnification method, or by means of the nodal slide, for different zones of the aperture isolated by diaphragms and to plot the variations of focal length with incident height on the same diagram as the spherical aberration.

Astigmatism and Curvature

For the measurement of astigmatism the object used should consist of a grid diagram having vertical and horizontal lines, preferably fitted in a collimator, and used with white light. The positions of the tangential and sagittal foci are then measured on the optical bench at each angle of obliquity, by the movement of the eyepiece required to bring the vertical or horizontal lines into sharp focus.

Distortion

The distortion should be measured at several definite settings of the focal plane and the setting for which the distortion is a minimum adopted as standard. The actual measurement is made by using a single line as object and measuring in a micrometer eyepiece the variations in the position of the image with angle of obliquity. If this test is carried out for different colours of light the transverse chromatic aberration can also be found.

Focometers

Other instruments are used in the manufacture and testing of lenses but possibly one of the most useful for general use is the focometer by which the focal length of a lens can be quickly and easily measured. Fig. I. 7 shows one such focometer, manufactured by the Precision Tool and Instrument Co. Ltd., for the measurement of the focal length of microscope objectives, while Fig. I. 8 shows a focometer made by the Pullin Optical Co. for the Stearman Optical Co. for measuring the vertex focal length of spectacle lenses. The general principle of both instruments and of all focometers is very similar, although the details naturally vary. In the usual form a collimator provided with a fine scale at the focal plane of a lens emits a beam of parallel light which is brought to a focus by the lens under test and the image formed is examined in an eyepiece having a scale at its focal plane. The sizes of the scales in the collimator and eyepiece are so proportioned that the focal length of the lens can be read off directly. In the Stearman focometer and in several other similar instruments the collimator is adjustable and is provided with some simple patterned graticule. By adjusting the position of the graticule converging, parallel or diverging light can be obtained and after passing through the lens under test the final image is seen in a fixed eyepiece. The focal length of the lens is then read from a scale attached to the moving graticule.

Fig. I. 7. Focometer for Microscope Objectives.

The whole subject of applied optics is very large and it is quite impossible within the confines of this chapter to do more than indicate the principles and to refer the reader to the standard works listed below for further information.

Fig. I. 8. Focometer for Spectacle lenses.

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CHAPTER II

SPECIAL CAMERAS

The application of photography to many specialised branches of science has led to the design of cameras and photographic equipment the existence of which is not generally realised. The essentials of a camera, such as the enclosed light-tight body, the light collecting and image forming lens, the exposure regulating shutter, and the light sensitive emulsion surface are retained but any of these essentials may be modified to meet special requirements. There is no logical approach to a description of this kind covering a large variety of instruments, nor will it be possible to include every variation or application, but the following sections will indicate the trend of development.

Photogrammetry

Photogrammetry is the name applied to that branch of science which deals with the application of photographic methods to measurement, and more particularly to surveying or map-making. The cameras and equipment used for these purposes must be capable of producing accurate results, or, in other words, such errors as are unavoidable must be systematic and capable of measurement. Among the cameras used for this purpose are the Air Survey Camera, the Photo-theodolite and the Kine-theodolite.

Air Survey Equipment

For survey photography from aeroplanes the camera is fixed in the aircraft with its axis vertical, or at a predetermined oblique angle, or multiple cameras with one vertical and several oblique may be used. As the aircraft flies over the ground successive exposures are made at predetermined intervals of time so that the terrain is covered by a series of overlapping photographs. Successive flights along parallel lines are then made until the whole area to be surveyed is completely covered by overlapping photographs. The amount of the overlap in the forward direction is usually about 60% with about 30% lateral overlap, and the overlapping portions form a succession of stereoscopic pairs from which, by careful measurement, the map is constructed. A number of very ingenious machines for the automatic drawing of maps, fully contoured, have been developed for use with air photographs.

Early air survey cameras used glass plates because of their rigidity but there has been a steady advance in the production of suitable film with minimum stretch and distortion characteristics, and modern

air survey cameras are designed to use this film. An example of a recently-designed air survey camera is shown in Fig.II. 1 and is the product of the Williamson Manufacturing Company of London, who have been pioneers in this work since the earliest days of air

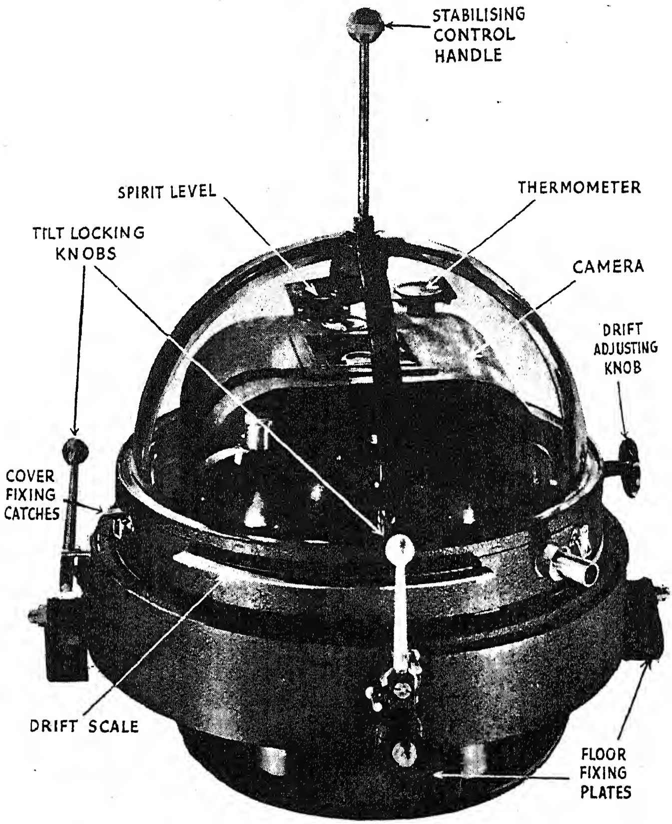

Fig. II. 1. Air survey camera—OSC Mk. I in mounting witn temperature control chamber.

photography. The camera is known as the OSC Mk. I and is descended from a long series of air survey cameras known as the "Eagle" cameras. The lens used in the OSC camera is normally a Ross 6 inch F/5.5 covering an angle of 95 degrees across the diagonal of the picture. This lens is an outstanding achievement of the firm of Ross Ltd., of London. The optical system of the camera which includes the lens and a glass register plate in the focal plane as one unit, is removable and interchangeable with other lens units of different focal lengths. The optical systems are calibrated for focal

length and distortion so that the angular relations between the positions of image points and the corresponding ground detail is known. The methods used for the calibration of cameras are described in books on Photogrammetry and Air Surveying and these methods can be applied to any camera used for accurate measurement.

The shutters used in air survey cameras are of the inter-lens sector type for short focus lenses, the diameters of which are not very great, and of the louvre type for the longer focal lengths where the diameters are such as to render inter-lens types unsuitable. These shutters are very much more robust than the usual shutters fitted to cameras since they are required to operate faultlessly thousands of times per day. In small sizes they are operated by means of a solenoid and in the larger types by motor. The versatile focal plane shutter cannot be used for survey purposes because of the distortion introduced by the finite time taken by the exposing slit to traverse the picture space. In addition, owing to the movement of the aircraft in pitch and roll, unknown and unmeasurable distortion can be introduced if the exposure is not made over the whole picture at once. The normal exposure times required, using fast film, is of the order of 1/300 second at F/11 in summer sunlight in Europe.

The magazine of the OSC and other air survey cameras contains 500 exposures each nine inches square with an inch between each exposure for recording a set of instruments at the same time as the main exposure is made. Fig. II. 2 shows the appearance of the record on the film of the instruments in the camera.

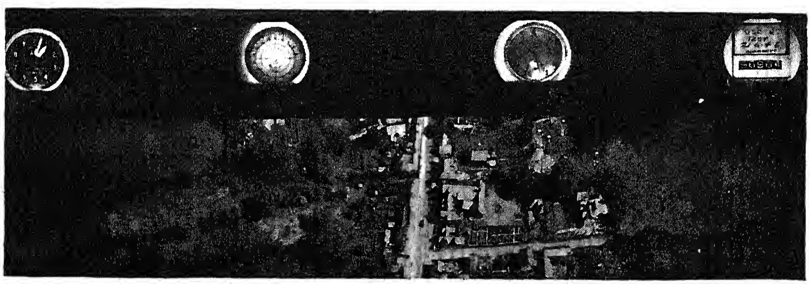

Fig. II. 2. Record of instruments, counter and data tablet, watch, level and altimeter, on a portion of an air survey photograph.

The camera is entirely automatic in operation and can be controlled by hand or electrically. For electrical operation an automatic timing control box is used in which, by merely turning a knob, any time interval between exposures from 2 to 60 seconds can be set. When

switched on the camera continues to make exposures at the set time interval without any further attention, warning lights inform the pilot and operator when the camera is about to make an exposure and a tell-tale shows that everything is functioning correctly.

The mounting shown in Fig. II. 1 is the latest type suitable for manual stabilisation and with a thermostatically controlled heated enclosure by means of which the functioning of the camera is ensured under all conditions of external temperature. The hot air used for heating the camera enclosure is frequently obtained from the exhaust of the engines and the air blast is first directed on the lens surfaces to prevent misting and then circulates throughout the enclosure. The camera is mounted in such a way that the centre of gravity, allowing for the transfer of the film mass, coincides with the intersection of the axes about which the camera swings in its mounting and the shock absorbers are carefully designed to prevent, as far as possible, the effect of vibration.

Other Air Cameras

A large number of other types of air cameras is in existence but all have been designed on similar lines. Owing to the continuous movement of the aircraft in its flight the exposure given must be very short and where the maximum resolution is required attempts are made to compensate for the movement by using film moving continuously at a regulated speed so that the image is stationary. In another form the whole camera is swung on its transverse axis to compensate for movement, and in others the lens is mounted on an eccentric mounting and traversed at the correct speed. In still another form of moving film camera the film is moved past a slit and a long strip of continuous photograph is obtained. To obtain the necessary stereoscopic cover, two lenses are fitted, one in advance of and one behind the slit so that two strips in correct stereoscopic relation are obtained. A specially designed stereoscope is used for examining this continuous strip.

To cover very large areas in the shortest possible time cameras with multiple lenses and multiple cameras are used, in at least one such installation the whole visible ground from horizon to horizon being photographed at one time. At the other extreme, long focus lenses covering relatively small angles are used where considerable ground detail at a large scale is required. The scale of a vertical air photograph is, of course, given by the ratio of the focal length of the lens to the height at which the photographs are taken.

Ancillary Equipment

The range of ancillary equipment used in map-making from air photographs is very large and complete. The long lengths of film are processed in automatic processing machines, the exposed film

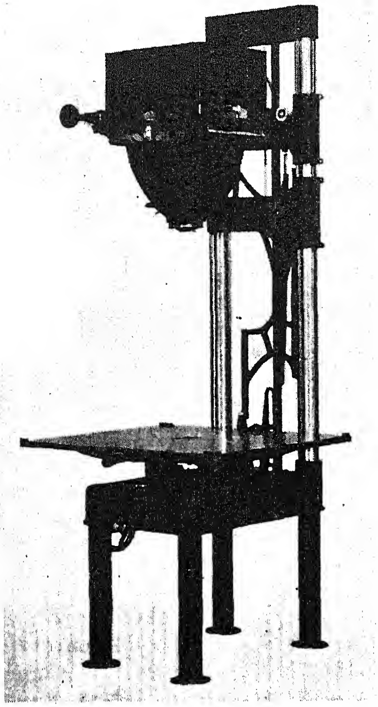

Fig. II. 3. Auto-focus enlarger with tilting easel used for air survey photographs.

being fed in at one end and fully developed, fixed, washed and dried before being delivered at the other end. Automatic printing machines are also used which deliver any number of prints, fully processed and dried, from each negative without any attention. The enlarger shown in Fig. II. 3 is provided with a tipping and tilting table and with tilting and sliding lens holder to enable rectified prints to be obtained from tilted photographs.

For the actual map-making a large variety of stereoscopes exists, of varying degrees of complexity, from the simple viewing stereoscope to the complex machine on which a fully contoured map can be drawn. Fig. II. 4 shows a multi-projector unit used to arrange a number of air photographs in correct relation to each other.

Photo-Theodolite

Photographic surveying on the ground has been practised for many years, particularly in mountainous country, for filling in the detail of complex mountain masses and ridges. Originally the cameras used were ordinary landscape types, but very soon the photo-theodolite was evolved. To meet the necessity for precision the camera was built solidly with a fixed relation between the lens and focal plane and with means for precise levelling to ensure that the photographic plate is vertical. Auxiliary optical systems built into the camera record the reading of the horizontal circle and in some instruments the vertical circle and level bubble are also recorded. A telescope for sighting the camera in the required direction is often mounted on top of the camera, and the whole instrument is supported on the usual levelling and centring theodolite base. The photo-theodolite requires the same calibration that any other measuring instrument requires. Since the number of photographs taken at any time is limited there is no necessity to use film, and plates with their many advantages are invariably used in photo-theodolites.

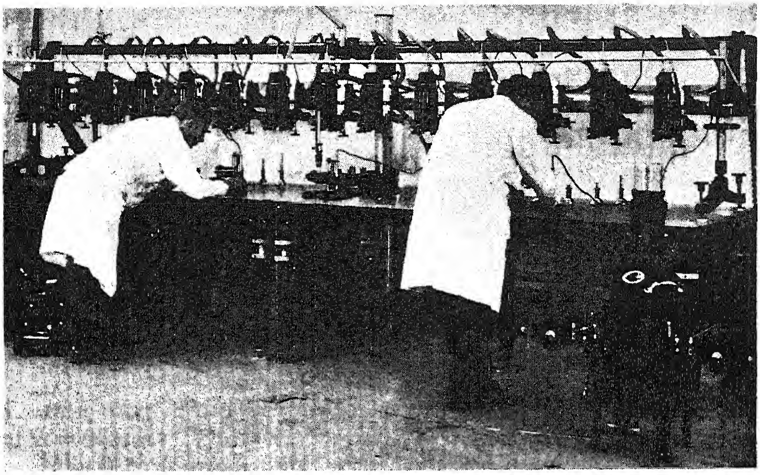

Fig. II. 4. Unit of fourteen projectors used to arrange a series of air photographs in correct relation to each other.

Kine-Theodolites

As the name implies, the kine-theodolite is simply a photo-theodolite in which a number of photographs are taken in rapid succession on film. The instrument is used for following aircraft and meteorological balloons and records on each frame the angles of elevation and bearing from a fixed datum line. The kine-theodolites are frequently used in pairs or groups of three or more on carefully surveyed bases so that the exact position in space of the aircraft or balloon can be accurately plotted.

The camera portion itself is of more or less standard form, using 35 mm. cine film, but the frame size is similar to that used in miniature cameras, namely 36 × 24 mm., and the maximum speed of taking is not usually more than four pictures per second. Single exposures can also be taken at will and the cameras can be synchronised in pairs or

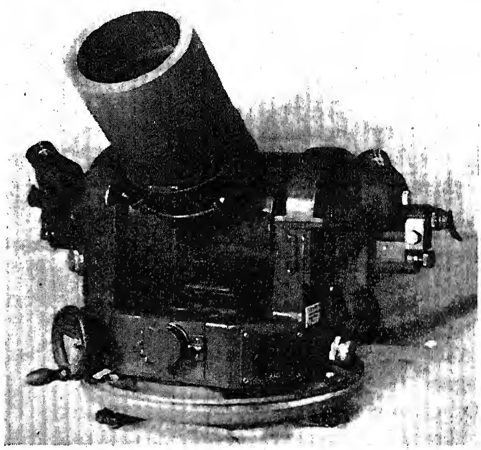

Fig. II. 5. Kine-Theodolite for recording successive positions of aircraft and balloons.

groups and with other apparatus. Rotating sector shutters usually used in cine cameras cannot be used, and some form of louvre shutter is fitted. Auxiliary optical systems are used to record on the film the readings of the horizontal and vertical circles and the whole instrument can be levelled in the usual manner. Viewing microscopes for examining the film form part of the equipment and these are provided with moving and rotating graticules to enable accurate measurements to be made. The lenses fitted are usually of long focus covering a comparatively small field and are specially made for high resolution to show a small object against a sky background. To enable the camera to be sighted on the object a complete system of sighting telescopes and control handles is fitted to the instrument. A modern form of the kine-theodolite is shown in Fig. II. 5.

Recording Cameras

Under this general heading cameras will be described which possess some distinctive feature differentiating them from normal cameras and which are essentially recording instruments. Probably

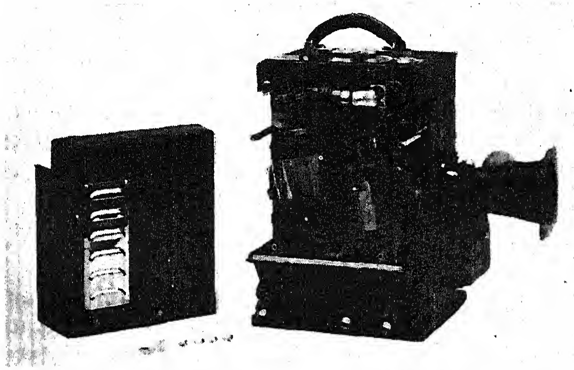

Fig. II. 6. Moving film camera for recording the traces on cathode ray oscillographs.

the most important kinds of recording cameras are those which employ a continuously moving film; these are used extensively for recording the indications of cathode ray tubes. The Avimo 35 mm. camera shown in Fig. II. 6 and the 70 mm. version are typical of such cameras. In cameras of this type there is no shutter, the lens remaining open and the exposure being regulated by the width of the slit past which the film is dragged. The speed of movement of the film can be varied over wide limits according to the speed of the phenomenon it is required to record. The 35 mm. camera uses a single lens, while the 70 mm. camera can be fitted with a pair of lenses so that simultaneous records of two separate phenomena can be obtained on the same film.

In one variant of the 70 mm. camera the normal lenses are replaced by cylindrical lenses, in front of one of which can be fitted a prism in such a way that a complex vibration can be resolved into two components at right angles and recorded. A small lamp or reflector is fitted to the vibrating article and the cylindrical lenses form line images of the light source at right angles to the slit in the focal plane of the camera. As the object vibrates the line images move along the length of the slit and the record on the moving film therefore shows the component of the vibration in the direction of the slit. The prism fitted in front of the second lens is a truncated right angle prism set with its principal plane at 45 degrees to the slit and so rotates the image that the component of the vibration perpendicular to the slit is converted into an image movement parallel to the slit.

When the phenomenon to be recorded is of very short duration a specialised instrument known as the drum camera is used. In this type of camera the film is wound round the periphery of a drum some three or more feet in diameter, and the drum is rotated at high speed past the slit. The drum takes either one length of film wound once round the periphery or several turns can be taken and the drum caused to move in the direction of its axis so that the film is correctly aligned with the slit. Extra film can be accommodated inside the drum and in one camera fresh film can be wound into position without opening the camera, the used film being taken up in a casette inside the drum. The lenses fitted in these cameras can be of any focal length. Fittings are provided to fix the smaller cameras to cathode ray oscillographs of standard makes or the camera can be built in as part of the apparatus.

For the recording of the readings of instruments and for mass radiography and the recording of documents on film, the cameras used are more or less normal in general construction except that the film magazines have a capacity of several hundred exposures and the shutter and film wind can often be operated from a distance. When contemplating any form of photographic recording for scientific purposes it is advisable to consult one of the larger photographic manufacturing firms for a suitable camera and technique, as the ordinary amateur camera can seldom work as efficiently as a specialised piece of apparatus.

Another form of camera used largely for the photography of aircraft during take off or landing, or for recording objects dropped from aircraft or projected from the ground over predetermined courses, consists in a stationary plate past which a moving slit is traversed at the correct speed. The moving slit is coupled to a sight used by the operator to follow the object and the camera shutter is operated automatically every time the slit moves its own width.

In this way repeated photographs are taken of the object in its trajectory and the movement can be analysed on the plate.

High Speed Photography

Other cameras of normal type used with intense flashes of extremely short duration have been used with great success for the photography of shock waves accompanying the flight of projectiles at supersonic speeds. The arrangement of lights can follow the well-known Schlieren principle to make the shock waves visible. It should not be forgotten that advantage can be taken of the intermittent nature of normal cinematography to obtain a stroboscopic effect for the study of machinery in motion. High speed cine cameras of almost normal construction are available taking photographs up to about 300 pictures per second, but for still higher speeds from 1,000 to 10,000 frames per second special cameras are necessary. In one form of ultra high speed camera the film is moved continuously through the gate and a large number of lenses arranged round the circumference of a rotating disc form images successively on the film, the speeds of rotation of the disc and of the film being such that the image is at rest on the film during the period of exposure. In another form the film is again moved continuously, but a single lens is used and the exposures are made by a rotating block of glass which acts both as the shutter and to keep the image stationary on the moving film. In still another form a series of mirrors are disposed round a drum and serve the same purpose as the rotating block of glass.

Unusual Cameras

Most normal cameras of the types generally available use lenses of which the focal lengths do not differ greatly from the length of the diagonal of the picture space. Lenses with a focal length much greater than the diagonal are described as of long focus and if the focal length is much less than the diagonal the lens is said to be of wide angle. Among long focus lenses, well-known telephoto types are supplied for the sake of compactness and such lenses up to 40 inches in focal lengths are readily available. Cameras fitted with long focus lenses are frequently used for scientific purposes where small angular deviations have to be measured; thus with a 40-inch lens, angles of the order of one minute correspond to one hundredth of an inch in the photograph and can easily be measured.

Short focus, or wide angle lenses, on the other hand, have many applications. The Ross F/5.5 wide angle lens with a field of 95 degrees has already been mentioned, but where such a large aperture is not required lenses at F/16 are readily available which cover angles of over 100 degrees, and at smaller apertures still wider angles can be obtained. In the special case where angles in excess of, say 120

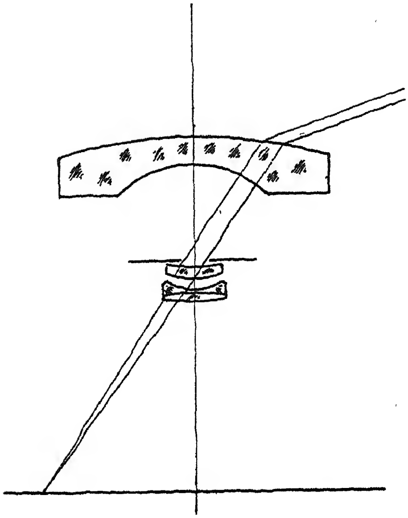

Fig. II. 7. Extra wide angle lens system.

degrees are required, if the plate is not to become infinite in size and if a reasonable quantity of light is to fall on the plate, some form of distortion must be introduced so that the whole hemisphere can be recorded on a flat plate. In fact the image must be a projection of the hemisphere on the plate. Several lenses with fields of about 180 degrees have been patented, but they are not generally made and have to be specially ordered. Fig. II. 7 shows the form which most of these lenses follow. The upper lens is used to bend the light downwards towards the lower lens and thus introduces the necessary distortion. The lower lens merely forms the image on the plate and corrects the defects introduced by the upper lens. Cameras fitted with lenses of this type have been used for recording cloud formations for meteorological purposes and for determining the total illumination reaching any part of a room from windows and skylights.

Since lenses of this type are not easily available several other means of obtaining similar results have been tried. In one variation a spherical mirror is placed on the floor and an ordinary camera, well stopped down, is fixed vertically over the mirror so as to photograph the virtual image formed in the convex surface of the mirror. For the best results the convex mirror should be figured from the spherical to a hyperboloid shape. Another, and very simple, means of obtaining extreme angles of view is to use a pinhole camera in which a glass hemisphere is fixed immediately behind the pinhole. Rays striking the diametral face of the hemisphere through the pinhole are refracted strongly and emerge normally from the spherical surface.

Toroidal systems capable of recording an all round view of the horizon are well known and one example is shown in Fig. II. 8. The type of photograph obtained from one of these toroidal lenses

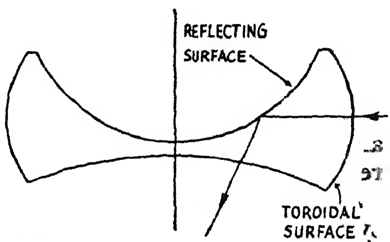

Fig. II. 8. A toroidal lens for all round view.

is shown in Fig. II. 9. It will be seen that both sides of the street as well as its ends are visible in the photograph. The use of the ordinary pinhole camera where perfect freedom from distortion is required should not be forgotten and with a pinhole of the order

Fig. II. 9. All round photograph taken with toroidal lens shown in Fig. II. 8.

of 0.01 inch and a plate distance of 1 inch, using modern high speed plates, the exposure required may be only a fraction of a second.

Returning to more normal types of camera we have the well-known panoramic camera in which either the lens itself swings about an axis passing through its back nodal point or the whole camera is rotated while the film is moved at the correct speed to ensure that the image is stationary during the exposure time. In addition to their use for taking photographs of school groups, these cameras have other applications, and in one variant the lens is fitted with an astigmatiser which exaggerates the vertical height of objects while retaining a normal horizontal scale. These astigmatising systems can take the form of a pair of cylindrical lenses forming a Galilean system in one plane only and fitted in front of the camera lens.

Finally, mention should be made here of the numerous Schmidt camera systems which are receiving considerable attention where the

maximum resolution is required. So far, Schmidt cameras have been used mainly for astronomical work and the system has been applied to the projection of television pictures. Essentially the Schmidt principle consists in the use of specially shaped corrector plates to correct the spherical aberrations of a concave mirror. It is well known that a concave mirror has very large longitudinal spherical aberration, but if it is used with a stop at the centre of curvature this is the only aberration present, provided the image is formed on a convex surface concentric with the mirror. By introducing a plate of special shape at the centre of curvature this spherical aberration can be almost entirely corrected, while the amounts of coma, astigmatism and chromatic aberration introduced by the plate are very small. The great advantage of the Schmidt system, and all its many variations, lies in the very large apertures that can be achieved even at long focal lengths. Apertures of the order of F/1 are not uncommon and F/2 is considered quite normal with diameters of 15 inches or more. Such apertures would be quite impossible in any lens system because of the difficulty of obtaining large pieces of good optical glass free from defects. The disadvantage of the Schmidt system lies in the fact that the focal surface must be spherical if the maximum resolution is demanded, as any attempt to flatten the field involves the introduction of some form of lens system with all its defects.

The application of photography to scientific work of all kinds has grown to such an extent, and the number of special cameras evolved to meet the demand has become so great that a complete description is impossible here. Enough has been said, however, to emphasise the necessity of using the most suitable type of camera for any specialised application.

Bibliography

The following books on Air Surveying may be consulted by readers interested in the map-making aspect of the subject. There are no books dealing specifically with cameras of the types mentioned in this chapter but the literature of photography in general terms is very complete and the Handbook of Henney and Dudley is the most comprehensive.

Surveying from Air Photographs. Hotine. Constable.
Air Photography Applied to Surveying. Hart. Longmans.
Photogrammetry. Edited Von Gruber. Chapman & Hall.
Aerial Photography. Winchester and Wells. Chapman & Hall.
Airplane Photography. Ives. Lippincott.
Handbook of Photography. Henney and Dudley. McGraw Hill.

CHAPTER III

ILLUMINATION AND BRIGHTNESS MEASUREMENT

The measurement of illumination and brightness, collectively referred to as photometry, is a fundamental requirement in many scientific measurements and calculations. Illumination and brightness are not the same, the first being the amount of light that falls on a given surface (from some outside source) and is independent of the nature of the surface, thus a black, white or coloured surface placed at equal distances from a point source of light are all equally illuminated. They are not, however, all equally bright and according to the nature of the surface light falling on it is partly absorbed and partly reflected, that which is reflected conferring on the surface the property of being bright.

Illumination is measured in terms of the fundamental unit, the lumen, which is $1/4\pi$ of the light emitted by a standard candle and it may be expressed as a lumen per square foot or foot candle, a lumen per square centimetre or phot, a lumen per square metre or lux, while units such as the mile candle are sometimes used in problems involving visibility ranges of light signals and the like.

Brightness is measured in terms of candle power per unit area, thus on the British system the unit is the candle per square foot or candle per square inch and in the metric system it is the candle per square centimetre, etc., while for exceedingly bright surfaces such as the crater of an arc or the sun, a possible unit is the candle per square millimetre. There are variations of such units according to the range of brightness that it is required to express.

Reflectivity is the reflecting property of a surface and may be expressed as the reflection factor which is the ratio of the light reflected to the light incident upon the surface. This may vary with the wavelength of the light and incident white light may be coloured after reflection and it may vary in intensity with the direction of incidence so that the surface will appear brighter when viewed from one particular angle than from another. A perfectly diffusing reflecting surface obeys Lambert's Law, i.e., the light reflected from each element of surface in any given direction is proportional to the cosine of the angle which that direction makes with the normal to the surface. In practice no surface obeys this law perfectly, but there are several surfaces which approximate to it very closely, e.g., one coated with magnesium oxide by condensation of the smoke from burning magnesium. A more portable and durable matt white surface is a piece of depolished pot opal glass. Such a surface is

constantly used in photometry for the conversion of brightness measurements into illumination measurements.

Visual Photometers—Design Features

The most precise method of photometry is that which employs the photometric bench in conjunction with standard lamps, but in many instances this technique proves to be much too inconvenient, and as a result a variety of more compact and portable instruments has been designed since 1792, when Bouguer first described a simple photometer. In all visual photometers there is presented to the eye a bipartite field, one part of which is illuminated by light from the source or bright patch to be photometered and the other part of which is illuminated by a calibrated lamp. Arrangements are made whereby the quantity of light from the calibrated lamp can be regulated in a known manner. The measurement consists in adjusting the brightness of the calibrated half of the field (the photometric field) to be equal to that of the unknown field. The bipartite field may be obtained in various ways, e.g., as in the Bunsen grease spot photometer head, the Joly block, the Ritchie Wedge and the Lummer-Brodhun head.

The amount of light reaching the photometric field may be controlled either by use of the inverse square law as with the photometric bench, by crossing Nicol prisms, by rotating sector discs, by graded neutral tinted filters or by various types of mechanical slits and apertures. These factors influence the compactness and accuracy of the instrument. For instance, an instrument involving the inverse square law will tend to be bulky, while one which uses neutral filters can be made small but, unless special care is taken, will tend to be less accurate.

Again it must be remembered that the human eye is an integral part of the instrument as it alone can make the judgment of the equality of the brightness in the two parts of the field. At high brightnesses the most sensitive part of the retina is at its centre or fovea, which subtends only a few degrees. At low brightnesses, such as 0.001 candle per square foot or lower, the centre of the eye becomes less sensitive and the parafoveal regions more sensitive to light, hence the whole field seen should subtend a much larger angle, for example from 15 to 20 degrees, so as to cover a large area of the human retina. Thus it is difficult to make a universal visual photometer, i.e., one which will cater for the measurement of brightnesses from 0.000001 to say 10,000 candles per foot, a range of brightnesses to which the eye is sensitive and which occurs naturally in going from a dark night to a sunny day. Such measurements are not infrequently required in meteorological and visibility problems.

To illustrate the ranges of illumination and brightnesses that sometimes have to be measured, the following figures are of interest.

Illumination on :	Ft. candles.
Dark night	0.00001—0.000001
Moonlight night	0.01—0.001
Cloudy day	100—50
Sunny day	12,000—1,000

Many of the ordinary problems of illuminating engineering fall in the range 1—100 ft. candles.

Finally, it sometimes happens that the surface or source to be photometered is at a distance and is inaccessible. In such cases it may subtend at the eye an angle of only a few minutes. To deal with this type of photometric problem a special class of instrument, the telephotometer, has been designed. This type of instrument involves special design features and often includes Maxwellian view (see below).

Some typical photometers illustrating the features described above will now be described.

Low Brightness Photometer

The main features of a low brightness photometer developed by the Admiralty during the War (Fig. III. 1) are that the calibrated lamp is placed at one side of a whitened lamp house which acts as a light integrator, and the effect is to illuminate an opal glass uniformly. Light from this uniformly bright opal passes through an iris shutter and illuminates a second opal glass which forms the photometric field of view. The view is obtained by looking binocularly through the clear face of a 2 inch

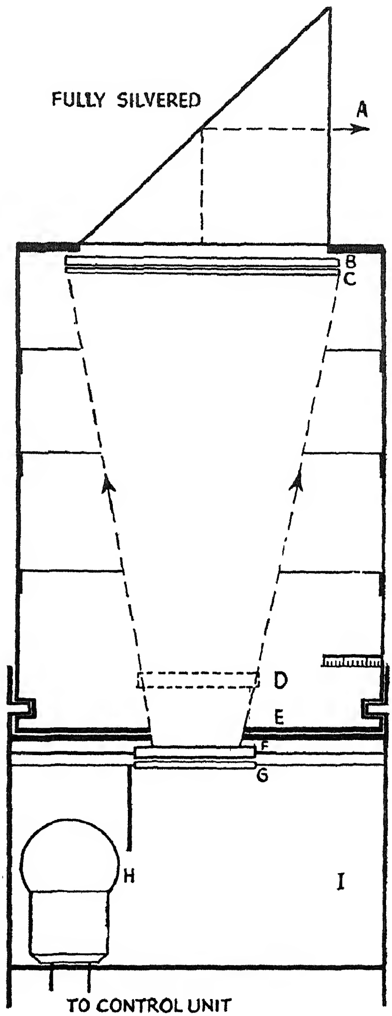

Fig. III. 1. Low brightness photometer.

A. Right-angled prism.
B. Fixed neutral filter.
C. Opal glass.
D. Lever-operated neutral filter.
E. Iris shutter.
F. Blue-tinted filter.
G. Opal glass.
H. Baffle.
I. Whitened lamp chamber.

right-angled prism which is fully silvered on its reflecting surface.

In use the instrument is held about 10 inches from the eyes so that it is seen against the surface of which the brightness is to be measured. The top portion of the instrument is held in one hand and the lower portion can be rotated so as to alter the aperture of the iris shutter, which in turn controls the brightness of the photometric field and is so designed that the logarithm of the brightness is proportional to the angle of rotation of the rotating sleeve. The range of the instrument can be extended by the use of neutral filters which can be inserted or removed by the operation of a lever. The object of the fixed neutral filter, of optical density about unity, is to reduce the intensity of any extraneous light that enters through the prism face to at least 1 per cent of its original value. Therefore when used out of doors the light from the sky behind the user does not introduce any error into the readings. The photometric field in this photometer is about 12 degrees ; the sharp edge of the prism provides a good dividing line between the photometric field and the field to be photometered. Binocular view of the field helps to eliminate eyestrain when used over long periods. The use of the blue glass next to the lower opal is referred to in the section below. The lamp control unit is the Wheatstone bridge type and is referred to in the section dealing with control units. The instrument may be made completely portable by fitting it with a six volt dry type accumulator. The range of the instrument is from 0.01 to 0.00001 candle per square foot.

Macbeth Illuminometer

The Macbeth illuminometer, which has a small field of view, is useful in the region of intermediate and high illumination, i.e., greater than about 0.1 ft. candle. It depends for its operation on the inverse square law. An opal screen is illuminated by a lamp

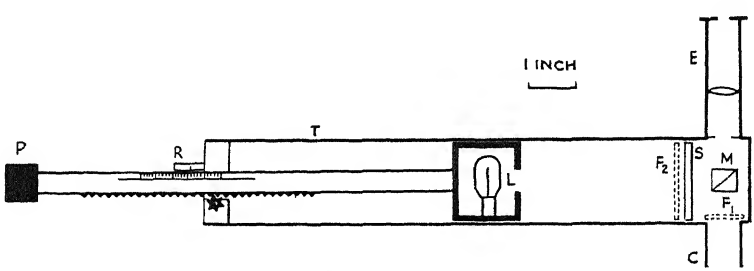

Fig. III. 2. Macbeth illuminometer.

E. Eyepiece.
M. Photometer cube.
L. Lamp.
S. Opal glass.
F_1F_2. Removable neutral filters.
T. Light-tight tube.
R. Scale.
P. Plug to control unit.
C. Open tube through which unknown field is seen.

which can be moved along a tube by means of a rack and pinion. The photometer head consists of a Lummer-Brodhun cube of the brightness or contrast type, which is viewed through an eyepiece. Photometric balance between the comparison field and the field to be measured, which is seen through the open tube, is obtained by movement of the lamp backwards and forwards. The normal range of the instrument is from 1—25 foot candles. This range may be extended to higher and lower values by the insertion of neutral filters on either side of the photometer cube. For the measurement of illumination the photometer is used in conjunction with a calibrated white surface.

The instrument may be provided with an aged and calibrated lamp controlled from a reliable unit such as the Wheatstone bridge. When so calibrated it retains its accuracy over long periods. Alternatively it may be provided with a simple control such as a voltmeter or ammeter and rheostat and checked at the time of use against an opal surface illuminated with a sub-standard lamp. The former method is to be preferred if the instrument is to be used away from a laboratory for long periods.

The Schuil Telephotometer

This instrument is designed for the measurement of the brightness of small distant objects illuminated by daylight. It is small and compact and is specially adapted for use from aircraft. The layout of the instrument is shown in Fig. III .3. It consists of a prismatic telescope of magnification 6 having an artificial exit pupil of 4 mm. In the focal plane of the objective is a very small comparison patch obtained by means of a photometer cube between the erecting prisms and the field lens. The comparison field is lighted from the opal surface of a lamp run at a fixed voltage and placed at the focus of the condensing lens. The photometric field is seen in focus in the main field of view of the telescope. The apparent field of the telescope is 50 degrees and the comparison field is in the shape of a shallow U 21 min. long and $11\frac{1}{2}$ min. high on the outside and 15 min. long and $5\frac{1}{2}$ min. high on the inside. The surface to

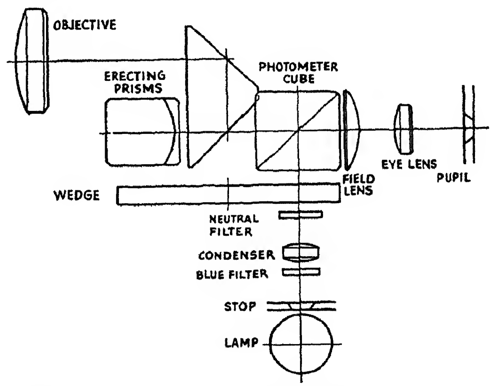

Fig. III. 3. Schuil telephotometer—optical system.

be photometered is brought into the hollow of the U (23 × 8.5 feet at one mile fills the hollow) and the brightness of the surrounding U can be varied by rotating a knurled head which controls a neutral wedge. The range of brightness is altered by means of neutral filters placed between the lamp and the wedge which are operated by a lever. The use of the blue correction filter is referred to in the section below.

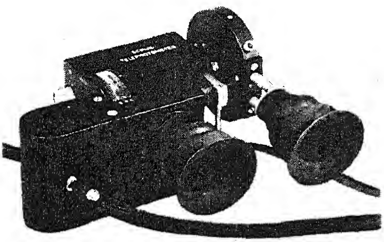

Fig. III. 4. Schuil telephotometer with inclinometer attachment.

The instrument can be used to measure brightnesses in the range 0.001—100,000 foot lamberts. For certain purposes it is fitted with an inclinometer attachment for use in aircraft. A photograph of the instrument is shown in Fig. III. 4.

The Photometry of Weak Point Sources—Maxwellian View

A useful method of photometry designed to measure sources of low candle power, or the brightness of small objects at a distance is that usually referred to as the "Maxwellian view". The principle is that if a lens or mirror be used to form a real image of an object at the pupil of the eye, the whole surface of the lens or mirror appears to have a uniform brightness equal to that of the original object surface multiplied by the transmission (or reflection) factor of the optical system and by a factor depending upon the relative distances from the lens (or mirror) of the object and the eye. The principle is illustrated in Fig. III. 5. By its use an extended field of view may

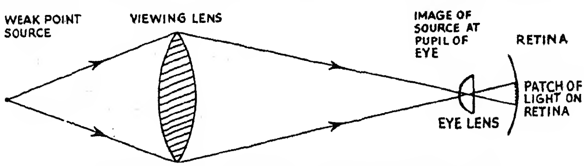

Fig. III. 5. Principle of Maxwellian view.

be obtained which can then be matched by a suitable photometric field. It is of importance to ensure that the eyepiece in the system does not act as a stop of variable aperture should the position of the image shift owing to some necessary displacement in the optical train producing it. It is advisable to arrange that the image is considerably smaller than the mechanical aperture of the eyepiece.

The use of the principle in the photometry of a low brightness source is illustrated in Fig. III. 6. In this arrangement the source to be measured is placed at the focus of a convex lens and the emergent

parallel beam falls on the lower half of a second lens which forms an image of the source at the pupil of the observer's eye. By means of an inclined mirror the upper half of the second lens is filled with light from a standardised source. A third lens has to be used with

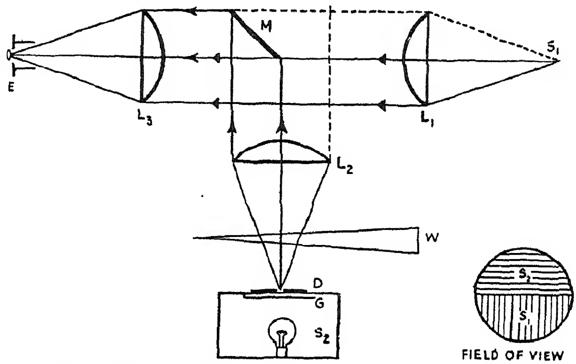

Fig. III. 6. Photometry of a weak point source.

S_1. Weak source.	W. Photometric wedge.
S_2. Lamp.	M. Plane mirror.
G. Opal glass.	L_1, L_2, L_3. Plano-convex lenses.
D. Small aperture.	E. Eye.

the standard source so that the light from it is parallel when it reaches the second lens. In this manner, images of both the unknown and the standard sources are formed at the eye pupil, and by Maxwellian view the eye sees a bipartite circular field : one semicircle illuminated by the standard source, the other by the unknown source. In practice the standard source will consist of a standard lamp illuminating an opal screen from which light is emitted through a small diaphragm. The source to be measured can be matched photometrically, in the bipartite field seen by the eye, by movement of the photometric wedge. Such an instrument can be used for the measurement of the brightness of stars and has been used successfully to measure candle-powers as low as 10^{-9} candle.

Portable Photometers—Reliability and Precision

Provided all the optical and mechanical details of a visual photometer are of the maximum efficiency then the ultimate limit to the precision of the instrument is the sensitivity of the eye to the brightness difference in the photometric field. The higher the brightness of the field the greater the precision of the photometric match. At high brightnesses a brightness difference of about 1.5 per cent is detectable. At lower brightnesses the minimum detectable difference progressively increases until at about 0.00001 candle per square foot it amounts to about 25 per cent. Thus at low field brightness

photometry is inherently less accurate. To obviate as much of this inaccuracy as possible it is very desirable to maintain the angular size of the field at a large value.

Slight differences in colour between the comparison field and the field to be measured tend to make the task of matching the brightnesses a more difficult one. For example, light from a tungsten lamp is yellowish compared with daylight and some people experience difficulty in deciding the point at which the yellowish field is equal in brightness to the bluish field of the daylight. If the photometer is intended mainly for use with one quality of illumination it is often desirable to insert a suitable filter between the lamp and the photometer head to match the colour of the light to be measured. Thus in the low brightness photometer and the telephotometer described above bluish filters have been inserted to convert the colour of the light from the tungsten lamp to that of natural light.

The reliability of a portable photometer depends entirely on the constancy of the calibrated lamp. Before calibration the lamp needs to be aged by running for about 100 hours at the rated voltage. The mounting of the lamp should be such that bad electrical contacts are unlikely to develop and such that the lamp does not alter its position when the instrument is jolted. The choice of the best method of ensuring that the lamp always runs at the same brightness is an important one. The choice lies between setting the current or voltage to a stated value or adjusting the resistance of the lamp to a constant value. The first two methods depend on either an ammeter or a voltmeter remaining in perfect condition through the life of the instrument. A 1 per cent change in the indication of the ammeter involves about an 8 per cent change in the brightness of the lamp, while a 1 per cent change in the indication of the voltmeter involves about a 3 per cent change in the lamp brightness. Thus, of these two methods, voltage control is preferable, though care must be taken with all electrical connections that poor contacts, which might alter the effective resistance of the lamp, do not develop.

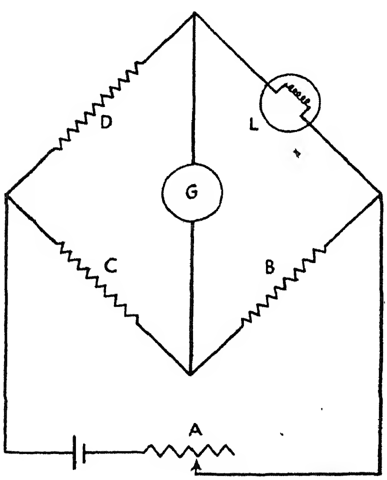

Fig. III. 7. Wheatstone bridge control for photometer lamp. B, C, D. Fixed resistances. A. Variable resistance. L. Lamp.

The third method of control is shown in Fig. III. 7. The lamp is placed in one arm of a Wheatstone bridge. The other resistances in the bridge are chosen so that

with the battery to be used the desired voltage is across the lamp. All connections must be soldered, and the resistances should have a very small temperature coefficient. The lamp is adjusted to its correct operating resistance by varying a rheostat until the galvanometer is at zero. This method eliminates the uncertainty caused by possible variations in the indications of the electrical instrument since the galvanometer is used only as a null instrument. The Wheatstone bridge proves to be the most effective control for a portable photometer. Its only disadvantage lies in the fact that a somewhat higher voltage accumulator is required to allow for the voltage drop across the bridge resistance in series with the lamp.

Photoelectric Photometers

The photoelectric cell affords a method of eliminating the human eye from photometry and reducing it to a problem of physical measurement. Two types of photocell are available for this purpose—the vacuum emission photocell and the selenium rectifier cell. Compared with the human eye the response of these cells to light of different wavelengths is markedly different. The response of the eye to different wavelengths is evaluated in terms of the luminosity sensation evoked when equal quantities of energy of each wavelength are incident on the retina. This relationship is exhibited as a curve in Fig. III. 8. To replace the eye perfectly the

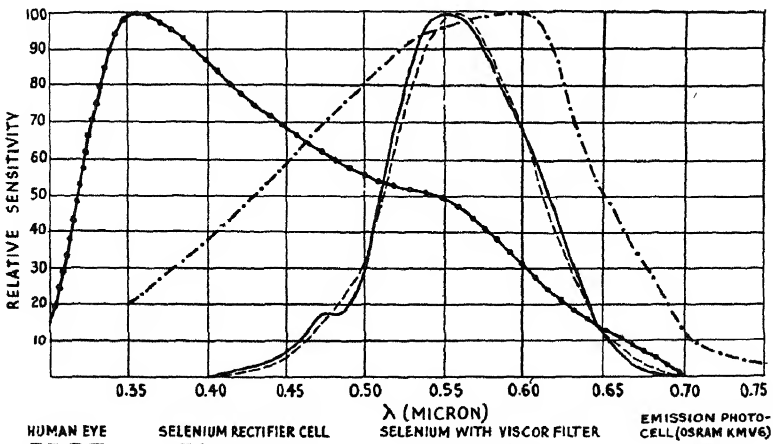

Fig. III. 8. Spectral sensitivities of eye and photo-cells.

photocells should have the same relative response as the eye, in terms of electrical output, at each wavelength throughout the spectrum. That the photocells diverge widely from this criterion may be judged from the curves of relative response given in Fig. III. 8.

In the circumstances where the spectral characteristics of the measured light are always the same the lack of agreement with the human eye is not serious, as a direct calibration with light of the required colour may be made. If the measured light differs in colour or in quantity of the light invisible to the human eye, which in the case of the emission photocell comprises the ultra-violet, then it is necessary to correct the response of the photocell to approximate to that of the human eye. For each type of photocell, various correction filters have been designed. The most satisfactory filter for the emission cell is a liquid one, while the most commonly accepted filter for the rectifier cells is the "Viscor" filter. The degree of correction achieved by the latter may be judged from Fig. III. 8. A full discussion of the problem of correction filters for photocells is given by Preston (see bibliography).

Selenium Rectifier Cells

The rectifier cell is pre-eminently suited for portable photometers. It needs only connection to a suitable ammeter to give a measurement of luminous flux. No auxiliary batteries are required. The luminous flux produces a current which, if the ammeter has a low resistance, is proportional to the intensity of the flux. The manner in which the current output of a 45 mm. diameter cell varies with the external resistance as the illumination falling on the cell is increased is shown in Fig. III. 9. If a linear variation of current with luminous output

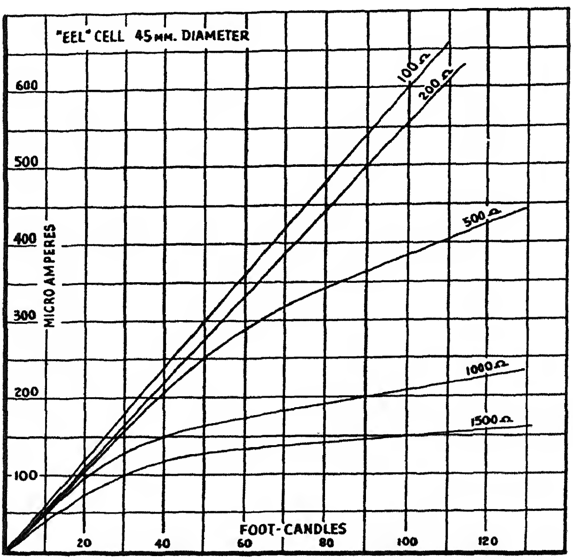

Fig. III. 9. Selenium rectifier photo-cell—effect of external resistance.

is required, then the resistance of the ammeter must be kept below about 100 ohms. In a multiple range instrument a series-parallel arrangement of shunts must be used so that the resistance offered to the photocell remains unaltered. This type of photocell may be used to measure illuminations of any high magnitude. At low illuminations a more sensitive meter such as a reflex mirror galvanometer, or alternatively a number of photocells linked in parallel, is required. By this means illuminations of 0.001 ft. candle can be measured. This can be regarded as the lower limit to its use, since the nature of the cell precludes valve amplification. For the illuminating engineer it is often the most convenient portable illumination meter. Various commercial models exist in pocket sizes in which the cell is built into the lid, which acts as a cover for the milliammeter. These instruments are calibrated for white (tungsten) light. Multiplying factors are given when required for use with other lights such as Sodium and Mercury lamps.

In some photographic exposure meters a rectifier cell is employed in conjunction with a meter of high resistance. This distorts the current output of the photocell to correspond more closely with the logarithmic exposure curve of the photographic plate. In these circumstances the calibration is not likely to remain constant.

It should be noted that the rectifier cell responds directly to incident light, i.e. it is primarily a measurer of illumination. If it can be placed in the plane of a surface receiving light, then the brightness of the surface can be estimated from the value of the incident illumination and the reflectivity of the surface. The cell very conveniently forms a telephotometer for daytime use if it is placed behind the focal plane stop of a suitable lens. It can be calibrated in terms of the brightness of the distant object.

Emission Photocells

The emission photocell, since it requires batteries of relatively high potential, is not as well suited to portable photometers as the rectifier cell, but its ultimate sensitivity is very much greater than that of the rectifier cell. The sensitivity of the latter is of the order of 500 micro-amperes per lumen, while that of the emission cell in conjunction with valve amplification can be raised to as high as 20 amperes per lumen.

The basic circuit for the direct-reading photometer employing an emission photocell (vacuum type) is shown in Fig. III. 10. The photocell is connected

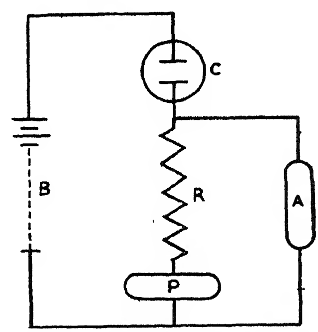

Fig. III. 10. Vacuum photocell used as a direct-reading photometer.
C. Photocell. R. High resistance. P. Potentiometer A. Amplifier.

in series with a battery, a very high resistance, and a calibrated potentiometer of negligible resistance. A D.C. valve amplifier or detector of small potential differences is used as a null indicator. With the cell in darkness and the potentiometer at zero, the indication of the amplifier is recorded. Then the light falls on the cell and the potentiometer is set to reduce the amplifier to its original value ; this procedure means that the net change in the voltage applied to the amplifier is zero. Consequently the voltage drop due to the photo-current in the resistance has been balanced by the voltage applied in the opposite sense by the potentiometer, and therefore the potentiometer reading is proportional to the light flux.

If the photocurrent is of the order of 10^{-8} amp, then a resistance of about 10^{8} ohms is required to obtain a voltage drop of 1 volt which can be balanced accurately by the potentiometer. This null method is preferable to the technique in which the indication of the amplifier is used to measure the voltage drop across the resistance, since in the latter method it would be necessary to rely on the amplifier remaining constant over a long period. The sensitivity of the arrangement depends ultimately on the value of the resistance, and when this becomes very large the valve connected to it must be of the electrometer type with a highly insulated grid. Using a 10,000 megohm resistor and a carefully designed circuit, such a photometer has been used to measure, with a precision of .5 per cent, an illumination of 2×10^{-6} foot candles. Full details of such a photometer are given in a paper by Preston.

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CHAPTER IV

INFRA-RED SEEING DEVICES

The human eye is sensitive only to a very limited region of the electro-magnetic spectrum which extends from the extremely short wavelengths of nuclear rays to the longest radio waves. The infra-red region lies, as its name implies, to the long wave side of the visible portion of the spectrum, and may be said to extend from 0.75 micron (1 micron = 0.001 mm.), where the eye has become almost completely insensitive, to the region of millimetre waves where the recently developed radio techniques of generation and detection become possible. In this chapter, however, we shall only concern ourselves with the near infra-red region which lies between 0.75 micron and 1.3 microns.

The Detection of Near Infra-Red Radiation

Infra-red detectors normally employed in the near infra-red are photographic plates and films, photo-emissive cells and photo-conductive cells. The photographic process has been extended to about 1.2 microns by adding suitable dyes to sensitive silver salts. It has the advantage of being an integrating process and gives a permanent record which is available for analysis at any time afterwards, but suffers from the disadvantages that liquid chemicals have to be used for development and that a short time always elapses after exposure before the negative is available, both of which are undesirable in a number of applications.

Photo-emissive cells usually consist of a sensitised cathode and an anode in a glass bulb, which is either evacuated or contains one of the inert gases, usually argon, at low pressure. When radiation of suitable wavelength falls on the cathode electrons are emitted, so that if the anode is maintained at a suitable positive potential a current flows which can be amplified and measured. Infra-red sensitive cells have cathodes consisting of complex caesium, silver and oxygen compounds—usually referred to simply as the Cs—O—Ag surface. The sensitivity extends from the ultra-violet to about 1.2 microns with a peak near 0.8 micron. One special form of photo-emissive cell is the "image converter", which will be described in detail later on.

Photo-conductive cells as used in the near infra-red usually consist of layers of either thallium sulphide or lead sulphide suitably sensitised by the addition of oxygen. When infra-red radiation falls on these substances, electrons are liberated for a short time, and although they

remain in the layer their presence as free electrons helps the passage of electric current when a voltage is applied across it. This increase of conductivity can be measured and thus used to detect radiation.

So far we have only dealt with the detection of infra-red radiation. A more important problem which cannot be solved by the photographic method is the instantaneous conversion of an invisible infra-red image into a visible one. There are methods for doing this, so far still in the laboratory stage, which make use of the photoconductive effect, but by far the most elegant and useful instrument for this purpose is the photo-emissive image converter, large numbers of which have been made and used in the last few years.*

Emission and Propagation of Near Infra-Red Radiation

All bodies at temperatures above absolute zero are at all times emitting thermal radiation. The quantity emitted is proportional to the fourth power of the absolute temperature of the emitting surface, and is spread over a waveband with a maximum emission at a wavelength characteristic of the surface temperature. A large percentage of the radiation from a very high temperature body such as the sun, lies in the visible region, whereas the maximum of the emission curve from a tungsten filament lamp at 2,800° K. is in the near infra-red (Fig. IV. 1). As the temperature of the surface is lowered the intensity of radiation decreases at all wavelengths and becomes more and more concentrated at wavelengths far removed from the visible region. At 500° C. the peak emission is near 3.5 microns and at normal temperatures near 10 microns.

From a study of Fig. IV. 1 one can make two important deductions. The first is that by combining a tungsten filament lamp with an infra-red filter (that is a filter which transmits a high percentage of the radiation in the near infra-red while completely absorbing the visible radiation) an efficient infra-red beacon or searchlight can be made. Secondly, since the sensitivity of a Cs—O—Ag surface extends further into the infra-red

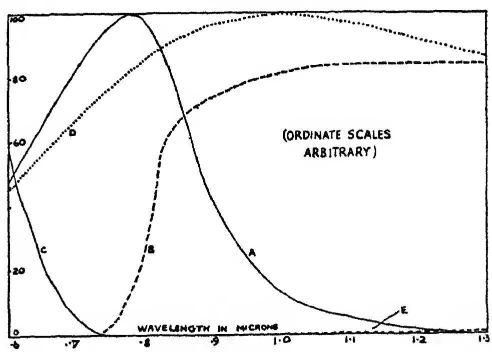


Fig. IV. 1.

Curve A. Spectral sensitivity curve for the Cs—O—Ag surface.
Curve B. Percentage transmission curve for a typical infra-red filter.
Curve C. Visibility curve for the eye.
Curve D. Spectral emission curve for a tungsten filament lamp.
Curve E. Spectral emission curve for a surface at 500°C. using the same ordinate scale as Curve D.

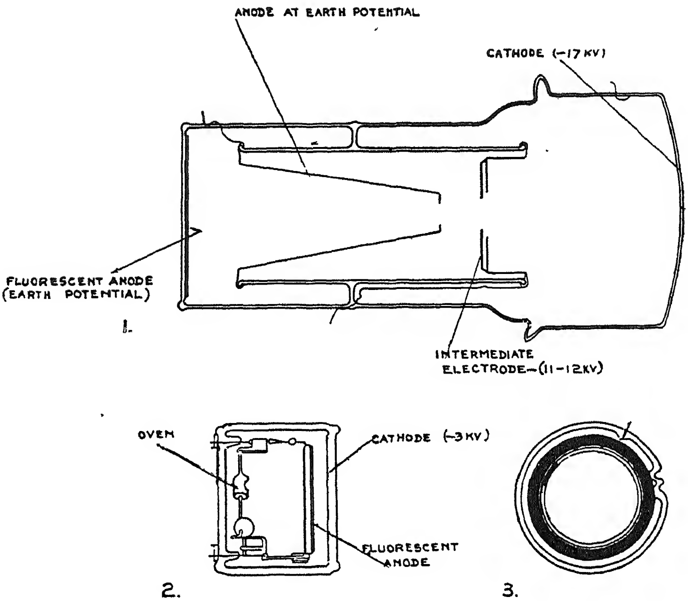
than the visibility curve of the eye, the former can "see" hot surfaces which are not hot enough to appear incandescent to the unaided eye. These factors form the basis of applications of viewing equipment sensitive in the near infra-red.

The propagation of infra-red radiation must now be considered. A clear atmosphere causes very little attenuation in the visible and near infra-red regions, but if the atmosphere contains suspended particles, scattering and absorption of radiation both occur, and the attenuation is then determined by the number of particles present and their size relative to the wavelength. If the particle size is small, selective scattering occurs according to Rayleigh's Law, which states that the intensity of the scattered radiation is inversely proportional to the fourth power of the wavelength. This results in an extremely rapid increase in penetration with increasing wavelength. It accounts for the redness of the sun when seen through horizon haze, where the shorter blue and green rays are scattered more than red rays, and also explains the long range photographs which have been taken in recent years with infra-red sensitive plates. It must be stressed, however, that all examples of extra infra-red penetration of this kind are obtained under conditions of relatively good visibility, when the size of the haze particles is small. When the visibility is poor, as in fog or cloud, the particles are large compared with the wavelength of infra-red radiation, so that the latter penetrates no more easily than visible light. This may surprise the reader, as the false belief that infra-red penetrates fog is very widespread.

The Infra-Red Image Converter

The infra-red image converter tube consists of a sensitised cathode of the Cs—O—Ag type and an anode arranged in an evacuated glass tube so that all electrons which are ejected from a particular point on the cathode impinge with a high velocity on a corresponding point on the anode. By covering the latter with a fluorescent material, usually willemite, the parts where the electrons strike can be made to emit visible light. If an infra-red image is projected on to the cathode, the number of electrons liberated from any small area of it is proportional to the amount of radiation falling on that area and thus when these electrons impinge on the anode a visible image is built up. Thus an invisible infra-red image has been converted into a visible (usually green) picture.

Although various designs of infra-red image converters existed before the Second World War they were really little more than laboratory curiosities ; the simplified, compact instruments which are available to-day were developed as a result of the concentrated effort directed to supplying equipment capable of fulfilling military requirements. Fig. IV. 2 shows two modern image converter tubes which are, in fact, standard German and British models.



(1.) THE SIMPLIFIED A.E.G. TUBE INTRODUCED IN 1943
(2.) R.G. TUBE (SIDE VIEW) } 1941
(3.) R.G. TUBE (END VIEW) }

Fig. IV. 2. Construction of two types of image converter tube.

The British R.G. tube (see also Fig. IV. 3) which was developed initially for use in signalling equipment, consists essentially of two plane parallel electrodes in vacuo with a potential difference of 3 to 7 KV. between them, and separated by a distance of about 5 mm. Electrons emitted from the cathode material, which is deposited on the inside surface of the front glass window, are pulled directly across to the anode. Because of the high field strength and the short distance between cathode and anode very little spreading occurs, so that a reasonably sharp picture is obtained. To simplify manufacture, a small oven, from which caesium is evaporated during the activation of the cathode, remains in the tube after completion, but is neatly folded back and held against the tube periphery.

In the German tube, electron focusing is employed, that is, the electrostatic field between the cathode and the fluorescent anode is not uniform but is arranged to bring all the electrons emitted from one point on the cathode to a corresponding point on the anode, even though they may leave the former at various angles to the normal.

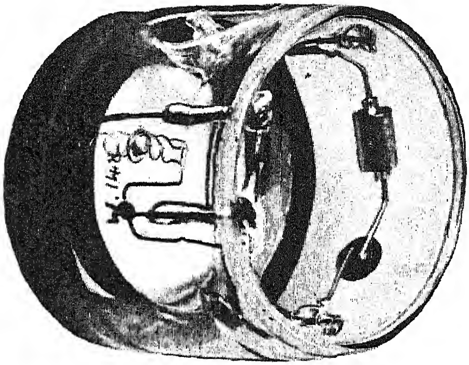


Fig. IV. 3. The R.G. image converter tube. (The letters R.G. were used as a code name during the war.)

The non-focusing tube is more compact and is more easily manufactured ; two very important factors in time of war. The image is free from distortion, and is equally sharp over the whole field. The definition near the centre of the anode is slightly better in the case of the focusing type tube, but is worse away from the central region. On the other hand the focusing type tube has certain fundamental advantages as a picture - forming device. These are :

(1) that the fluorescent image on the anode is inverted relative to the infra-red image on the cathode (electron optical inversion) ;
(2) that a higher voltage difference between cathode and anode can be maintained ; and
(3) that by suitably designing the intermediate electrodes the fluorescent image can be reduced in size (electron optical reduction).

Each of these factors will now be considered.

The electron optical inversion results in a simplification of the associated optical systems. If a simple objective lens is employed, the image formed on the cathode is inverted, hence the fluorescent picture is upright and can be viewed through a simple positive eye lens. In the case of the non-focusing tube, an extra inverting lens or its equivalent is needed, either in front of or behind the image converter tube, thus adding to the weight and size of the instrument. For many applications, for instance where a distant infra-red beacon marking some objective is to be picked up, the fact that the image is upside down is of no consequence, so that simple objective lenses and eyepieces are employed even with the non-focusing tube. The instrument shown in Fig. IV. 4 is of this type.

Since the cathode and anode can be much further apart in the focusing type tube, a greater potential difference can be applied between them. This is possible because the field strength in any part of the tube, but particularly in front of the cathode, does not become so great that field emission occurs, i.e., that electrons are pulled from the cathode even when no infra-red radiation falls upon

it. The higher voltage imparts a higher velocity to the electrons arriving at the anode and hence produces a brighter fluorescent image. At low image brightnesses this is particularly important, as the ability of the eye to see the details of the image is a function of its brightness, so that the greater voltage means that more detail can be appreciated by the eye. It is for the same reason that the third factor, namely electron optical reduction, is important.

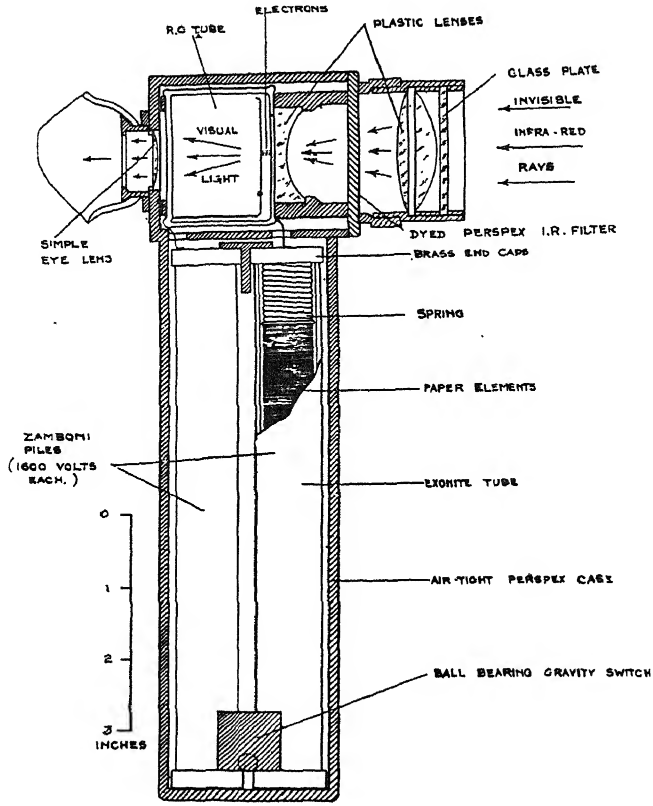


Fig. IV. 4. The R.G. image converter type BR/U3, a hand-held instrument used for detecting distant infra-red beacons.

The complete image converter consists essentially of an objective lens or mirror to produce the infra-red image on the cathode, the image tube itself, a viewing lens or eyepiece, and a high voltage source, usually of the vibrator type. It is not intended to describe here the many optical systems which have been employed. They vary from the 24 in. diam. lens-mirror system employed in a proto-

type German image converter which, in conjunction with a large infra-red searchlight, was intended for coast-watching, to the small plano-convex lenses of some pocket-size R.G. receivers. Fig. IV. 4 shows the construction of an instrument which has been particularly valuable for military use. An interesting feature of this equipment is that it incorporates a dry pile type of primary battery as the H.T. source, which is made possible because of the very small currents (about 10^{-10} amps) which are required. The pile consists of a large number of paper discs each coated on one side with tin foil and on the other side with manganese dioxide and pressed together by a spring inside an exonite tube. A single unit, $6\frac{1}{2}$ in. long, $\frac{3}{4}$ in. diameter, containing 1,300 discs, gives about 1,200 volts, and has an internal resistance of approximately 7,000 megohms. The piles are compact and very light; they are simple to manufacture, require no maintenance, and have an almost unlimited life. They cannot be used in all image converters, however, because in some types, e.g. night driving equipment, the current required to produce a bright picture is much greater than the pile can supply.

Applications of Infra-Red Image Converters

Military Applications

As one might expect the military applications of infra-red image converters are more striking than those of peace. They can be considered under two main headings:

(1) For carrying out operations in complete darkness without resource to visible light, and hence with added security.

(2) To locate invisible targets for shooting at night.

The first category includes night driving of vehicles with infra-red filters covering their head-lamps and with the driver looking ahead through an image converter. Fig. IV. 5 shows a photograph taken

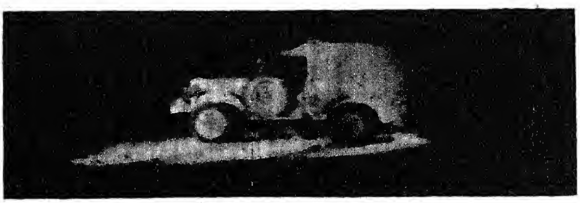


Fig. IV. 5. View of an Army truck taken in complete darkness through an R.G. image converter used for night driving.

through one half of a binocular driving equipment incorporating the R.G. tube. With this equipment, tanks, trucks, etc., can be driven with safety in complete darkness. On roads, speeds up to 30 m.p.h. can be achieved, and an encounter with such a vehicle is a hair-raising

experience to the uninitiated. Secret signalling and recognition devices are also included. For example, compact lightweight image converters used in conjunction with coded infra-red beacons were fitted by the Royal Air Force to night flying aircraft as a means of distinguishing friendly aircraft from those of the enemy. Another interesting device which found application during the war consisted of a small, lightweight infra-red beamed lamp and image converter combined. This transmitter-receiver combination was used in conjunction with small glass tetragonal prisms, sometimes known as "corner cubes", which exhibit the useful property of returning any radiation which falls on their hypotenuse face in exactly the same direction from which it comes; so that the image converter, which is fixed to the lamp and is always directed along the beam, collects some of the returning radiation, and the prism is seen as a bright spot in the centre of the field of view. These small prisms could be detected in the image converter at ranges of a thousand yards or so, and could be used to direct the observer towards them, during darkness, with complete secrecy.

Image converters can be used in two ways to assist snipers and gunners at night. The first method involves the combined use of a source of infra-red radiation and an image converter as a gun-sight. Examples of this are the German Vampire shown in Fig. IV. 6 and

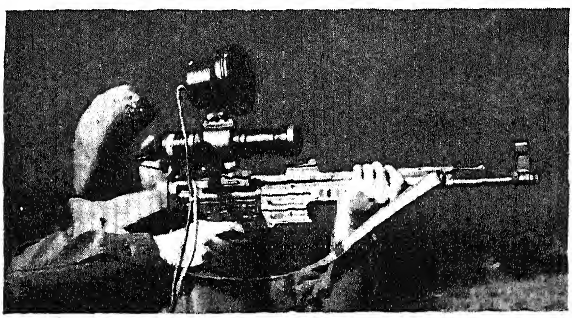


Fig. IV. 6. The German "Vampire". An infra-red lamp is mounted on top of the image converter. Batteries to supply current to the lamp and an H.T. unit are carried in a rucksack.

its British and American equivalents. Under good conditions useful ranges of the order of seventy yards can be achieved with the Vampire. Anti-tank guns used in conjunction with much heavier and more complex infra-red equipment with a range of several hundred yards were also manufactured by the Germans.

The second method of using infra-red image converters makes use of the radiation emitted by the target itself, and has been used for aircraft location. The red hot or nearly red hot exhausts of

aircraft can be detected from a considerable range unless they are well shielded. Since, however, the radiation does not penetrate clouds, and a considerable degree of shielding of the exhausts is possible, the method is not a reliable one.

Other Applications of Image Converters

The non-military uses of infra-red image converters are of a very specialised nature. Obviously they are of value if it is desired to watch something or someone during darkness without using visible light, and a number of applications of this kind are known. For instance, zoologists have recently used the equipment for examining the nocturnal behaviour of rats, and biologists have studied the behaviour of the human eye during conditions of low visible illumination.

Probably one of the most important applications is in the manufacture of those photographic materials which are only sensitive in the visible region ; these can be viewed through an image converter when illuminated by suitably screened lamps, and thus can be manipulated without any danger of fogging. Spectroscopists have used the equipment as a means of extending the "visible" spectrum from 0.7 micron to 1.2 microns, and astronomers have now a rapid means for examining the infra-red emission from celestial bodies.

The suggestion has also been made that police might find a use for the equipment, but from Press reports it appears that criminals, rather than the police, have taken the initiative in this field. Another more likely possibility is that infra-red image converters may be useful in hospitals for viewing patients during darkness when switching on an ordinary light would disturb them.

Picture Forming Equipment Sensitive to Longer Wavelengths

When the image converters described above are used during darkness a source of near infra-red radiation has to be employed to illuminate the objects viewed, unless they themselves are at a high temperature. Bodies at normal temperature emit very little radiation in the wavelength region to which these instruments are sensitive, but they emit copiously in the 10 micron region, that, is where the wavelengths are about ten times longer. Obviously if an image forming device can be developed which is sufficiently sensitive to 10 micron radiation, "seeing in the dark" will become a reality, objects being discriminated by differences in their surface temperatures.

Detectors which are sensitive to this radiation have been known for a long time. They include thermocouples and bolometers, and the more recently developed pneumatic detectors, and are characterised by the fact that their response is dependent on the heating effect of the radiation which they absorb. Relative to 'photo-detectors',

such as the Cs—O—Ag surface, they are sluggish and not very sensitive and attempts to use them in picture forming equipment have not been very successful. If, however, new detectors of 10 micron radiation with higher sensitivity and speed of response can be developed, a picture forming device may follow.

Such equipment would be of very great value in scientific research. It would provide, for instance, a means of obtaining 'temperature pictures' of engines and engine parts under test; the spectroscopist would be able to 'see' the fundamental vibration spectra of molecules; indeed there are possible applications in most branches of science. The difficulties which have to be overcome to develop such an instrument in a convenient form are very great but they do not appear to be unsurmountable.

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SECTION 2

ASTRONOMICAL AND NAVIGATIONAL INSTRUMENTS

CHAPTER V

ASTRONOMICAL

A few astronomical instruments were dealt with in *Scientific Instruments*, and this chapter carries the subject a stage further, though there is no suggestion that a complete list has been given, and only the more important instruments have been dealt with. Readers would find it an advantage to read the previous book just referred to, and in particular Section I which deals with optical instruments. Some knowledge of the properties of lenses and concave mirrors used in astronomical telescopes is assumed, and if any readers are not conversant with these they will find the necessary material in *Scientific Instruments*.

While some of the explanations have been brief, and many details have been omitted, readers will easily understand the main principles underlying the working of the astronomical instruments which are dealt with in this chapter.

The Coelostat

As its root name implies (*caelum*, the sky or heavens, and *stat*, stands still), the coelostat is an instrument for making the heavens appear to stand still, and has important applications in solar observations. Before describing the instrument it is necessary to say something on the mounting of telescopes (see also *Scientific Instruments*, pages 102-3). Small telescopes are often mounted so that they have two movements in a vertical and a horizontal direction—known as movements in altitude and azimuth, respectively. These two movements are sufficient to align the telescope on any celestial object, but to maintain the object in the centre of the field it is necessary to adjust the telescope by using the slow motions in both altitude and azimuth, an operation which is comparatively simple for small telescopes but more difficult for the larger ones. Astronomical telescopes of moderate size are mounted differently from the smaller alt-azimuth type, and a brief description of the mounting follows.

In the equatorial mounting there are also two axes, as with the alt-azimuth, but one of these, known as the polar axis, is parallel to the axis of the earth, and the other, known as the declination axis, is perpendicular to the polar axis. The polar axis always points towards the pole of the heavens which, in the northern hemisphere, is less than a degree from the pole star. If the telescope is pointed to any star in the heavens it is possible to keep it aligned on the star by one movement only round the polar axis, this movement being in a direction opposite to that of the earth's rotation, that is, from east to west. The rate of turning must be the same as that of the

earth in its daily rotation, that is 360° in 24 hours or 15° an hour, and the telescope is turned by a clockwork driven by a weight or electrically. It is impossible to secure absolutely the same rate of rotation as that of the earth, so that adjustments by the observer are necessary from time to time. Fig. V. 1 shows an equatorial mounting, *AB* being the polar axis and *O* the declination axis. The explanation under the diagram is sufficient for the present purpose.

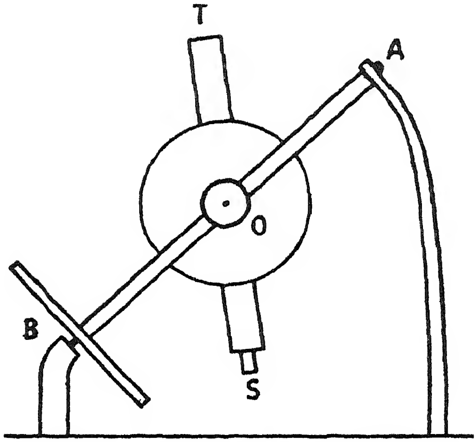

Fig. V. 1. Diagram of a telescope mounted equatorially. The polar axis *BA* points to the pole of the heavens and by rotating the telescope *TS* around this axis and the declination axis *O*, it can be set on any object. One movement round the polar axis then suffices to maintain the telescope pointed to the object. This is one of several forms, but the principle is the same in all cases.

Instead of a moving telescope there is a great advantage if the telescope is fixed and a rotating mirror is made to reflect the image of the celestial object on another fixed mirror which in turn reflects it down the telescope. A coelostat (Fig. V. 2) consists of two plane mirrors, one of which is turned on an axis once in 48 hours—not once in 24 hours as is done with a telescope equatorially mounted. The reason for this is shown from Fig. V. 3 (a), where *MM* is a plane mirror on which a ray of light *LP* falls at the point *P*. The plane through *LP* lies in the plane of the paper and the mirror can be rotated on an axis perpendicular to the plane of the paper. By a well-known principle in optics, the angle *LPN* between the incident ray *LP* and the normal *PN* at *P*, is equal to the angle *NPR* between the normal and the reflected ray. The angle between the incident and reflected ray is there-

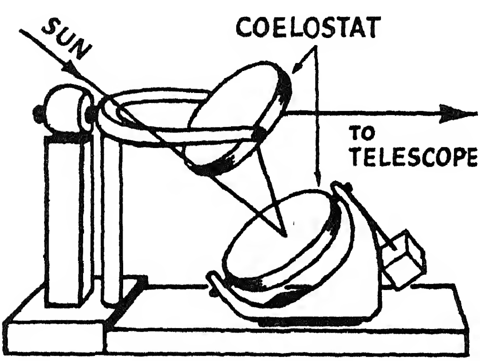

Fig. V. 2. The coelostat. The lower mirror can rotate and the ray of light from the sun is shown reflected by it to the upper mirror which reflects it to a telescope.

fore $2\,LPN$. If the mirror is turned in the plane of the paper through an angle α, the ray $L'P$, parallel to LP, will now make an angle $L'PN' = LPN + \alpha$, with the normal, and the reflected ray PR' will make the same angle with the normal (Fig. V. 3 (b)). Hence the angle between the incident and reflected ray is $2\ (\mathrm{LPN} + \alpha)$. As a result of the rotation of the mirror the deviation of the reflected ray is, therefore, 2α, and if the ray reflected from the mirror is to complete a rotation of 360° in 24 hours, the mirror must be turned round once in 48 hours.

The first stationary telescope which Dr. G. E. Hale established at Mt. Wilson was of the horizontal type, but this proved unsatisfactory because the layer of air heated by day was too close to the telescope and caused unsteadiness of the images. A tower telescope was then constructed, the first one being 60 feet long, and this was succeeded by another 150 feet long. The sunlight is admitted into the telescope a long way above the heated ground and steady images are produced. Another advantage of this kind of telescope is that, unlike the horizontal type, it does not bend, thus obviating the danger of giving distorted images. Such fixed telescopes permit the use of long-focus objectives which form large images of the sun.

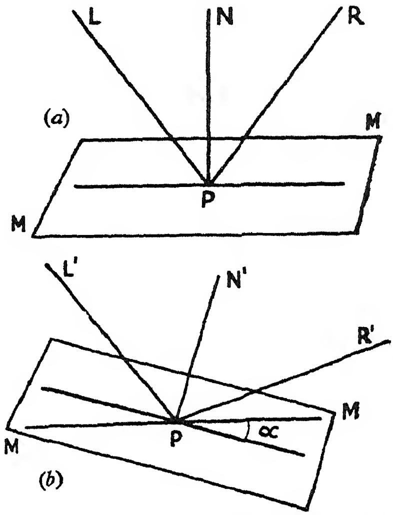

Fig. V. 3. Showing why the moving mirror in the coelostat must be rotated once in 48 hours, not once in 24 hours as in the case of a telescope mounted equatorially.

The coelostat is in the dome at the summit of the tower and is driven by one of the usual methods employed for equatorial mountings, but does not require so much power to drive it as a telescope, and a spring actuated driving clock is frequently used. The image of the sun is reflected by the rotating mirror on to the fixed plane mirror, which in turn reflects it downwards to a 12-inch objective underneath. This objective forms an image of the sun at a distance of 150 feet in the laboratory at the foot of the tower. A well, about 80 feet deep under the laboratory, has a grating unto which the sunlight is directed, and it is then returned to the laboratory, dispersed into spectra, the effective length of which partly depends upon the size of the telescope, and may be hundreds of feet from blue to red. The size of the image of the sun which is formed by the objective of 150 feet focal length is obtained as follows. The diameter

of the image bears the same ratio to the diameter of the sun as 150 feet does to an astronomical unit—the distance of the earth from the sun. Substituting 860,000 miles for the diameter of the sun and 93×10^6 miles for an astronomical unit, the diameter of the image is easily found to be a little under 17 inches. There is an obvious advantage in obtaining such a large image of the sun, which would not be so easy to accomplish by using the ordinary type of telescope.

The Photoelectric Cell

The action of the photoelectric cell depends upon the power of electrons to conduct a current of electricity and also upon the fact that electrons are released from potassium or any of the other alkali metals by the action of light. The number of electrons released is proportional to the intensity of the light, and hence the strength of the current, which depends on the number of electrons, measures the intensity of the light which releases the electrons.

In Fig. V. 4 the light from a star falls on the glass tube, the inner surface of which is coated with potassium. A current is passed from the battery through the interior of the bulb; the strength of the current, which is measured by means of a delicate galvanometer *G*, varying according to the number of electrons in the bulb. The photoelectric cell is the most sensitive instrument used in the measurement of the brightness of a star or in the fluctuations in its magnitude.

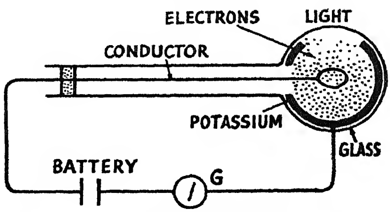

Fig. V. 4. The photoelectric cell for measuring the intensity of the light from a star.

Different types of the instrument have been constructed and some have been designed to give very great sensitivity. A. E. Whitford added amplifying tubes such as are used in radio work, and the small current which passes through the cell when the light of the star falls on it is amplified. It has been estimated from experiments with a candle at a distance of a mile, that this instrument, attached to the 100-inch telescope at Mt. Wilson, could detect the light of a candle 3,000 miles away, if it were not for the absorption of the light by the atmosphere. By means of this extremely sensitive instrument it has been shown that the Nebula in Andromeda is about twice as large as previous photographs indicated. This has been ascertained by the radiation emitted from the outer portions of the nebula which are not photographable.

The well-known effect of light in altering the resistance of selenium has been utilised in the "selenium cell". The cell is attached to the

eye-end of a telescope and the light from a star is allowed to fall upon it. A current from a battery passes through the cell and a galvanometer, and the brightness of different stars can be compared by reading the deflections of the galvanometer in each case. It has neither the sensitivity nor the practical advantages, however, of the photoelectric cell.

The Heliometer

This instrument, sometimes known as *Dollond's heliometer*, consists of a telescope, the object glass of which is divided into two halves along a diameter. One half can slide along another and thus two separate images of the sun can be produced. Very accurate measurements of the sun's angular diameter can be obtained by the instrument, the principle of which is easily understood from the following explanation.

In Fig. V. 5 S is the sun and O and O' the optical centres of the two halves of the objective. Each of these halves will form an image of the sun, and the lenses are separated until the two images touch each other. The upper half lens O' forms an image of the upper limb A of the sun at b, and the lower half lens O forms an image of the lower limb B also at b. Hence $AO'b$ and BOb are straight lines and the angular diameter AbB of the sun, which is the angle ObO' in the triangle ObO', is easily measured because OO' is known and also the perpendicular from b on OO', this perpendicular being the focal length of either half lens.

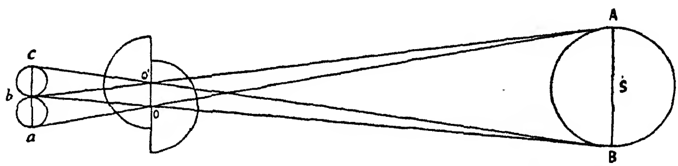

Fig. V. 5. The heliometer showing the two halves of a lens, one of which can slide over the other.

In actual practice two readings are taken, the first when the two halves of the object glass are in the position shown, and the second when the halves are interchanged, so that O is brought to O' and O' to O. Half the difference of the scale readings gives the separation of the two halves of the object glass.

The heliometer is also used to measure the angular distance between two stars or between a minor planet and a star. In this case the instrument is adjusted so that the image of one star formed by one half-lens coincides with that of the other star formed by the other half-lens. Before the images can be brought into coincidence the direction of separation of the two halves of the object glass must be parallel to the great circle through the two objects. This is

effected by rotating the object glass as a whole and the orientation can be read off from a graduated circle. The orientation and separation of the lenses having been adjusted until the images of the stars or other objects are brought into coincidence, the positions of the two half-lenses are then interchanged. The object glass is then rotated through 180° and the operations are repeated. The angular separation between the objects can thus be determined with a good degree of accuracy.

The Filar Micrometer

This instrument is used for measuring the diameters of the planets, the surface features of the moon, and the separation of double stars. It consists of a circular plate which is graduated from 0° to 360°, and is attached to the eye-end of the telescope. The field of the micrometer contains two spider-webs *CD* and *XY* fixed at right angles to each other, and also another movable web *EF* parallel to *CD*, actuated by a micrometer drum. The whole apparatus, together with the eyepiece of the telescope, can be rotated so that the webs (or wires) can be set in any required direction across the field of view. A graduated circle—the *position circle*—measures the angle through which the eyepiece has been turned, and gives the *position-angle*, an explanation of which is given later (see Fig. V. 6).

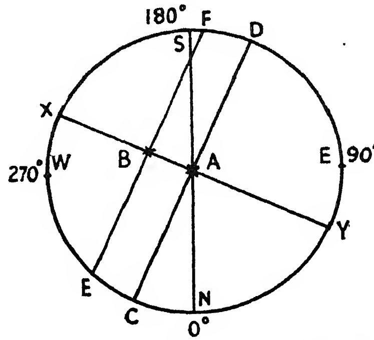

Fig. V. 6. The filar micrometer showing the two fixed wires *CD* and *XY* and the movable wire *EF*.

Suppose we want to measure the angular separation between the two components *A* and *B* of a double star, the primary being *A*. The telescope (mounted equatorially) and the micrometer are adjusted so that *A* appears at the intersection of *XY* and *CD*, while *XY* also passes through the other component *B*. The wire *EF* is then moved by the micrometer drum until it passes through *B* and the micrometer reading gives the separation of *A* and *B* in terms of the micrometer scale. To find the angular distance between the stars in seconds of arc it is necessary to know the number of seconds corresponding to one turn of the screw, and this can be determined by observing two objects of known separation and then calculating how many seconds of arc correspond to a turn of the screw.

The instrument also gives the position-angle of the fainter star. The position-angle is the angle between the line joining the components and the meridian of right ascension passing through the primary. In other words it is the angle between the lines *XY* and

NS, where *NS* is the N.-S. line through *A*. This angle is measured from 0° to 360° on the position circle, the zero point being at the north point of the field. The angle is reckoned towards the east and is the angle *NAY* in the diagram. Notice that an astronomical telescope produces inverted images, so that *N* at the foot of the diagram is north and the east is on the right-hand side of the diagram.

The Blink Microscope

This instrument is used to detect new and variable stars and also the proper motions of stars. It would be difficult to compare two plates of some particular portion of the heavens, taken at different times, each containing many thousands of stars, to see if one plate contains a star not in the same relative position on the other plate. This difficulty is overcome by the blink microscope, the principle of which is as follows.

The two plates for comparison are mounted side by side, and by the use of mirrors or prisms the same portion of either of them can be brought into the field of view of a low-power microscope. The plates are adjusted so that when they are viewed simultaneously the star images on each of them are superposed. There is an arrangement for illuminating first one plate and then the other at the rate of three or four times a second, and thus the two plates are seen in rapid succession apparently in the same place, not both at one place as in the stereoscope. So long as there are no new stars or so long as no stars have altered in brightness between the exposures of the plates, the operator has the impression that he is examining a single plate, but if any of the stars have varied in brightness or if there have been new stars between taking the plates, they will blink in and out, easily revealing their presence amongst all the other stars.

The blink microscope has been used very successfully for detecting the proper motions of stars. Those that have an appreciable proper motion blink in and out on the plates taken after a long interval, whereas others remain steady.

The planet Pluto was discovered in 1930 by Tombaugh at the Lowell Observatory, Arizona, by using the blink microscope. He found that one of the star-like points photographed on March 22nd had changed its position the next night. This change could not have taken place in such a short time from the proper motion of a star, and it was certain that the object was a comet, an asteroid or a planet. After two months' observation the mathematicians calculated its orbit, which was that of a planet, at a mean distance of nearly 40 astronomical units from the sun.

The Gerrish Drive

The Gerrish Drive was devised in 1900 by Prof. W. P. Gerrish, Harvard College Observatory, to provide a simple control for astronomical instruments, and Fig. V. 7 shows a modified form devised

by Hanson, and now used at Harvard. An electric motor is geared to a worm and wheel, to which is attached the telescope, and the speed of the motor is controlled by the pendulum of a clock. The pendulum carries a magnet *A*, and in the vertical position this magnet lifts the armature *B* and, opening the contact switch *C*, breaks the ten-volt circuit. When the circuit is broken, the armature *H* drops so far from the electro-magnet that it cannot be pulled back even when the circuit is restored, as the pendulum passes the vertical position. When the armature *H* drops, it closes the power switch *F* and the driving motor starts. A cam *J* geared to the motor returns the armature to its original position and it is held there by the ten-volt magnet until the pendulum returns to the vertical position and the circuit is broken again.

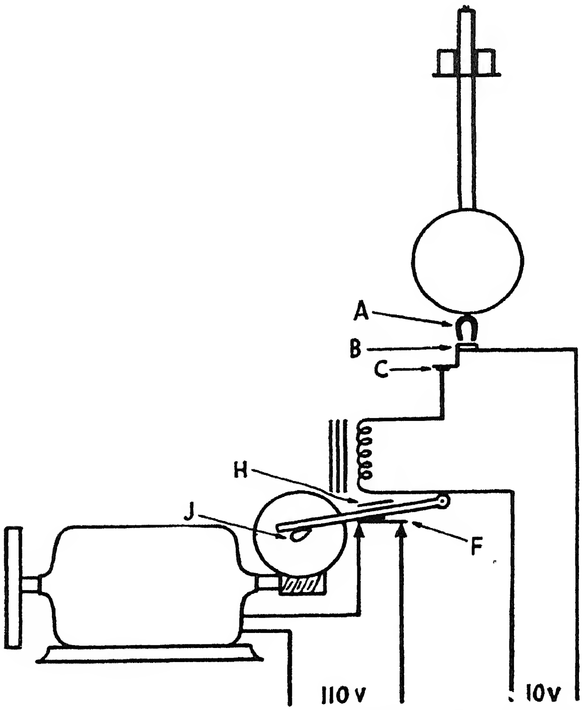

Fig. V. 7. The Gerrish drive. A full description is given in the text.

Imagine that the motor is going too fast. In this case the cam will rotate faster and cut off the power soon after the pendulum has released the armature *H*, and as the interval during which the power stroke is able to act is reduced, the motor will go more slowly. If

the motor is driving slow, the cam will not operate the switch F so soon and the power stroke is lengthened, so that the motor will go more quickly.

The drive can operate on A.C. as well as on D.C. and does not require frequency or voltage control of the electrical power. It is possible to regulate the rate of the clock by increasing or decreasing the load on the pendulum, which raises or lowers its centre of gravity.

The later design of the Gerrish drive has a photoelectric cell instead of the magnet switch. As the pendulum cuts off the small beam of light shining on the cell, this allows the pendulum to swing free without doing any work in lifting the armature.

Absorbing Wedge

In astronomical work it is frequently necessary to compare the magnitude of a star with that of another star in the same field, the magnitude of the latter having been previously determined, so that the magnitude of the first star can be easily ascertained. In many cases, however, the two stars are not sufficiently close to be seen at once in the same field, and in such circumstances the light from each star can be reflected into the field of the same telescope by mirrors suitably arranged for this purpose. The two images are then equalised by inserting in the beam of one star a calibrated wedge which transmits all the light at one end and is practically opaque at the other end. The wedge can be a piece of dark glass ground into the form of a wedge or it may consist of a piece of plane glass over which some metal has been evaporated in such a manner that there is a gradual variation in opacity. The wedge must be calibrated before use and by advancing it in the path of the brighter source of light until equality of illumination is observed, the intensity of one source in terms of the other is obtained, and hence the magnitude of the star under consideration.

It is important that the wedge should be neutral, that is, while it alters the intensity as the beam of the star enters it in different positions, it must not change the colour of the star image. If this condition is not fulfilled, fictitious results for the magnitude of the star will be derived. It should be said, however, that the requirement of strict neutrality to colour is not easily obtained.

Lyot Coronagraph

Until comparatively recent times astronomers were able to observe the corona only during a total solar eclipse. The great difficulty in attempting to observe it at other times lies in the fact that the emission lines are only one-hundredth as bright as the full moon and hence cannot be easily observed against the background of the sun. The Lyot coronagraph, called after Lyot of the Paris Observatory, has

overcome this difficulty by producing an artificial eclipse and by a number of devices which are described and illustrated in the accompanying diagram (Fig. V. 8).

The objective lens of the telescope must be as near to perfection as possible, and is mounted some way down the tube which is blackened inside. The objective casts an image of the sun on the

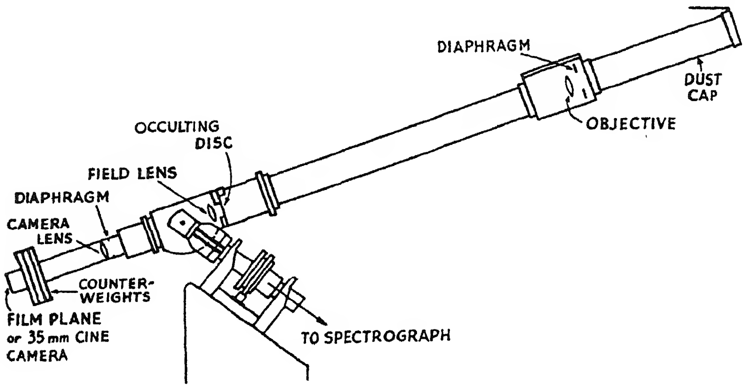

Fig. V. 8. The coronagraph. See text for description.

occulting disc which produces an artificial eclipse within the telescope. In front of the disc there is a tilted flat mirror which reflects most of the intercepted sunlight to one side, where it is trapped. Behind the disc is a field lens which focuses the objective lens on a camera lens, the diameter of which is slightly smaller than the objective image, the diffraction at the edge of the objective being thereby cut off. The camera lens throws the focused image of the sun and disc on the photographic plate, or spectrographic equipment can be used instead of the photographic plate. A very necessary part of the apparatus is the arrangement of circular diaphragms in various places to trap scattered light.

The apparatus must be used in a very clear atmosphere, and to minimize undesirable atmospheric effects mountain tops are essential. Lyot made the 9,400 foot ascent of the Pic du Midi to secure good observations, and two other coronagraph stations in operation, one at Arosa in Switzerland and the other at the Climax, Colorado, are very elevated, that in Colorado being more than 11,000 feet above sea level.

The Chronograph

This instrument has various forms, the two most common of which are the barrel chronograph and the tape chronograph. It will be sufficient to describe the principle of the former.

The barrel chronograph consists of a cylindrical barrel, covered

with paper, which turns slowly by clockwork at a uniform rate about its axle. A pen, mounted on a carriage which is traversed slowly along as the barrel turns, describes a spiral on the paper. At regular intervals, usually every two seconds, a clock causes the pen to flick slightly to one side, a current passing through the armature of a small electro-magnet from which the pen is supported. Definite intervals of time are thus automatically recorded by the clock on the paper. When an observer sees a star cross the vertical wire of his telescope he presses a button which completes a circuit and causes a current to make the pen flick to one side and to leave a mark on the paper. By comparing the position of this mark with that made by the action of the clock, the time of transit can be found with great accuracy. Generally, a number of reticules is used, and the time when the star crosses each of these is recorded. The average of the readings gives a more accurate result than a single reading.

The Microphotometer or Microdensitometer

This instrument is used to register the variations in the intensity of light with wavelength of the photographed spectrum. The photographic plate, upon which the stellar spectrum is recorded, is carried across a narrow scanning slit of light by means of a screw, geared to which is a roller covered with sensitive photographic paper. As the screw moves the plate the roller moves through a certain arc, and as the spectrum plate moves, the intensity of the transmitted light varies with the density of the portion of the spectrum beneath the slit image. This light falls on a photocell, a description of which has just been given, and the variations in intensity with wavelength of the photographed spectrum can be measured. By using an amplifier the small currents from the photocell are amplified and fed into a galvanometer by whose deflections the corresponding variations in the spectral density are indicated. An auxiliary light beam, reflected by the swinging galvanometer, is focused on the sensitive photographic plate, and thus the continual variations of the densities of the spectrum are recorded.

The Spectroheliograph

If an image of the sun is formed by means of a telescope and the light from one part of this image passes into the slit of a spectroscope, we shall obtain a spectrum of the light emanating from a narrow line on the sun. This line on the sun corresponds to the narrow line of light which enters the spectroscope. If now we use a second slit and place it on the spectrum so that the light from one of the hydrogen lines (or of any other lines we may wish to select) only is allowed to pass through, we see merely a narrow strip of the sun illuminated by the hydrogen line which it emits. Successive

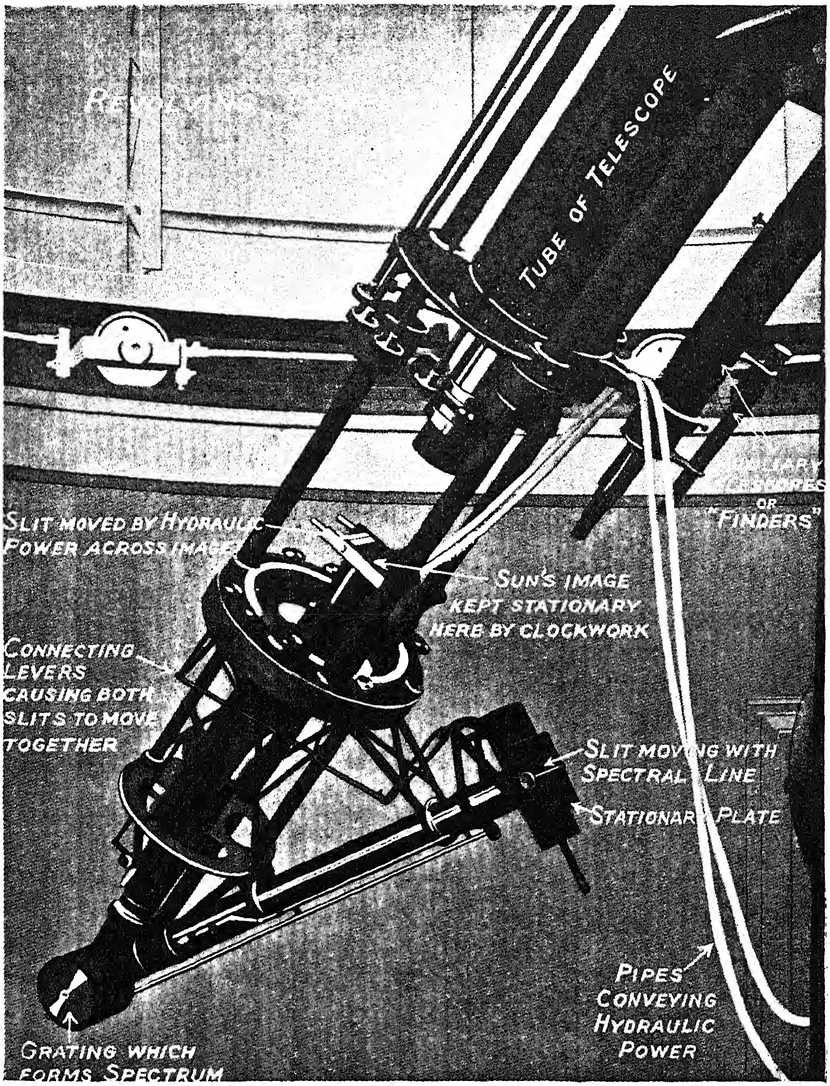

Fig. V. 9. The Spectroheliograph. A spectrum of the sun is formed in the usual manner by the use of a slit and grating, and then a second slit is placed exactly over one of the dark absorption lines of any selected element, so that all light is excluded from the photographic plate except the single ray due to that element. If the sun's image is focused on the first slit and both slits are moved simultaneously in the same direction, a composite picture is built up which shows the whole of the layer due to the element, hydrogen, sodium, or whatever line may be selected. The picture is virtually formed by placing together a large number of narrow strips of the solar image.

strips of the sun's surface can be viewed in the hydrogen light if the first slit is moved across this surface and also the second slit is kept over the hydrogen line. If these strips are photographed, a composite picture of the sun in the hydrogen light only is obtained. This is the principle of the spectroheliograph which provides a picture of the sun in light coming from one chemical element. Spectroheliograms taken in different lights—say calcium and hydrogen—give entirely different pictures of the sun and provide the spectroscopist with much valuable information about the conditions existing on the sun. (See Fig. V. 9.)

Another instrument which fulfils the same object is the *spectrohelioscope*,* in which a small area of the sun is viewed by the eye in light of one colour. If an observer uses an eyepiece to watch a strip of image drift across his field of view he will find it difficult to form a mental picture of the surface of the sun, but by utilising the principle of the persistence of vision it is possible for him to see in the eyepiece a built-up picture of the solar surface. This is done by making the slits oscillate rapidly backwards and forwards in unison.

There are various types of the spectrohelioscope but the principle is the same in all—the persistence of vision. In some forms the slits are fixed and the eye-point and a portion of the solar image are caused to traverse them in unison by refraction through square glass prisms. These prisms are mounted, one immediately in front of each slit, and are rapidly rotated about a common axis by an electromotor.

Not only does the spectrohelioscope afford a built-up picture of the sun ; in addition, it enables the observer to calculate the line-of-sight velocities of prominence either at the limb or when seen on the solar disc as dark flocculi. This is done by moving one slit relative to the other or moving it optically by interposing a glass-plate which is turned slightly on an axis parallel with the slit. By refraction this shifts the spectrum line by a small but known amount and the measured Doppler effect then provides the data for calculating the line-of-sight velocities.

The Schmidt Camera

An ordinary reflecting telescope has a very narrow field over which star images are sharp, and outside this field the images are distorted by a defect known as "coma" (see *Scientific Instruments*, p. 14). This imposes serious limitations on the large reflectors and is often a great disadvantage. Thus, the 100-inch reflector at Mount

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*For a full description of the instrument see *The Astrophysical Journal*, Vol. LXX, No. 5, December 1929, where Dr. G. E. Hale explains the construction and working with copious diagrams. See also *The Journal of the British Astronomical Association*, Vol. 48, No. 6, in which Mr. F. J. Sellers, F.R.A.S., describes his spectrohelioscope with oscillating slits.

Wilson has a coma free field of just over 7 minutes of arc and the 200-inch reflector will show stars free from coma over only half this area. The Schmidt telescope possesses the great advantage of completely eliminating a coma, thus allowing a much larger field to be viewed.

The essential components of the instrument are a spherical mirror (which is much easier to construct than a paraboloidal mirror) of short focal length, and a thin glass correcting plate of varying thickness which is placed in front of the mirror. It deviates the outer rays sufficiently to bring them to a true focus and at the same time it avoids errors at the edge of the field.

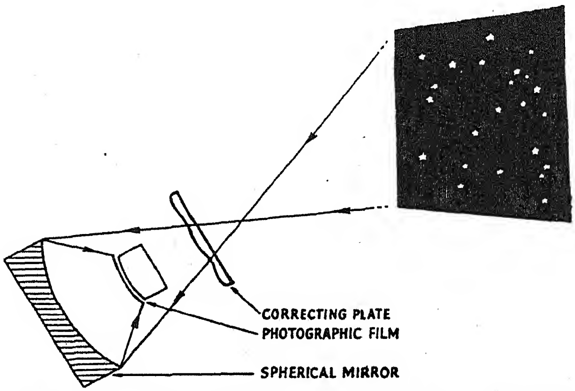

Fig. V. 10. The Schmidt camera which gives a wide field with high resolution. The correcting plate eliminates all coma, thus enabling a very large field to be viewed

The spherical mirror (Fig. V. 10) of very short focal length receives the light through the correcting plate placed at the centre of curvature of the mirror. The usual type of mirror in reflecting telescopes is a paraboloid, which brings parallel rays to a point focus. A spherical mirror suffers from the defect of spherical aberration, which is the failure of the light falling on the outer zones of the mirror to come to the same focus as that falling on the central zones. The Schmidt correcting plate obviates the necessity for parabolising the mirror and eliminates the coma, thus making a large field possible, slight variations in the thickness of a thin plate of glass taking the place of slight variations in the depth of the mirror.

By the use of the correcting plate the spherical mirror can have a very short focal length, and thus a wide field of view and a low focal ratio are obtained by the instrument. Cameras have been constructed with focal lengths less than their diameters, thus allowing the production of bright images of extended objects. The Schmidt camera has been responsible for showing that many faint nebulae

extend far beyond the limits previously believed to exist on the evidence of photographs taken with older equipment. It is the fastest astro-camera consistent with wide field, and yields the best photographic images yet known.

The focal surface lies on a sphere whose radius is the focal length of the system, and hence the photographic plate or film must be curved to fit this surface. This is one disadvantage of the Schmidt camera, but the difficulty has been partly overcome by the use of a *field-flattener*. In one form this consists of a plano-convex lens equal in diameter to the linear field to be covered, and placed with its plane side close to the photographic plate. The spherical convex side of the lens has a radius about one-third of the focal length of the Schmidt.

The above description of the instrument enables the reader to understand its main principles, but there are various modifications that have been introduced to render it more effective. These are too numerous to describe here, but details can be found in specialised books on astronomical instruments. (See also Chapter II.)

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The most modern book is *Telescopes and Accessories*, by George Z. Dimitroff and James G. Baker. (The Harvard Books on Astronomy, J. & A. Churchill Ltd., 104 Gloucester Place, Portman Square, London.)

CHAPTER VI

METEOROLOGICAL

Meteorology is the study of the physical properties of the earth's atmosphere. It is one of the most international of the sciences and one whose importance is being ever more widely recognized. It is indeed only comparatively recently that meteorology has been regarded as an exact science and our knowledge of its fundamental processes is still far from complete. This knowledge, and our ability to forecast the weather, will increase as meteorological instruments improve. The outstanding value of accurate forecasting to aviation, agriculture and in fact to most of our industries has led, and is still leading, to much instrumental development work.

The oldest meteorological instrument is probably the wind vane, dating back over 2,000 years. Barometers, hygrometers and thermometers for ground observations first appeared in the 17th century, but it was not until the late 19th century that serious attempts were made to explore the conditions of the upper atmosphere. It is here that the most spectacular advances have been made in recent years, and there is reason to expect considerable improvement in weather forecasting when the present network of stations making upper air observations is enlarged and equipped with a more uniform standard of instruments.

General Considerations

Meteorological instruments may be divided roughly into four classes: (a) general instruments, (b) special research instruments, (c) instruments using radio, and (d) aircraft instruments. The radio instruments are dealt with in Chapter VII, and research instruments are rather beyond the scope of this book.

The chief requirements of the general and aircraft instruments are accuracy—an accuracy of 0.2% of the range is frequently called for—combined with simplicity, robustness, reliability and cheapness. Meteorological observers may be situated in very remote places and for them an instrument that continually required skilled attention for repair and maintenance would be virtually useless. Many observers have not received any special instrumental training; hence the call for simplicity. The value of a series of meteorological observations over many years depends on the reliability and constancy of the instruments—many series have been vitiated by repeated changes of instruments which may have introduced discontinuities at the times of the changes.

The earliest and most fundamental instruments are eye-reading, in fact the eye itself is the most important instrument in meteorology. Recording instruments are, however, essential for many purposes and recorders have been developed for most of the meteorological elements. The most common recorder is that in which the sensitive element moves a pen up and down a chart which is driven about a vertical axis by a clockwork or electric mechanism, the period of a complete revolution being generally either 24 hours or a week. Further details about recording instruments will be found in Chapter XIX.

The exposure of meteorological instruments is of prime importance. Temperature and humidity especially have steep vertical gradients near the ground, and to ensure that observations at different stations are comparable it is essential that the instruments should be mounted at the same height. A standard method of protection from radiation is also very desirable. The Stevenson screen, which is illustrated in Fig. VI. 1, is in general use in this country for housing thermometers and hygrometers. It is a wooden box,

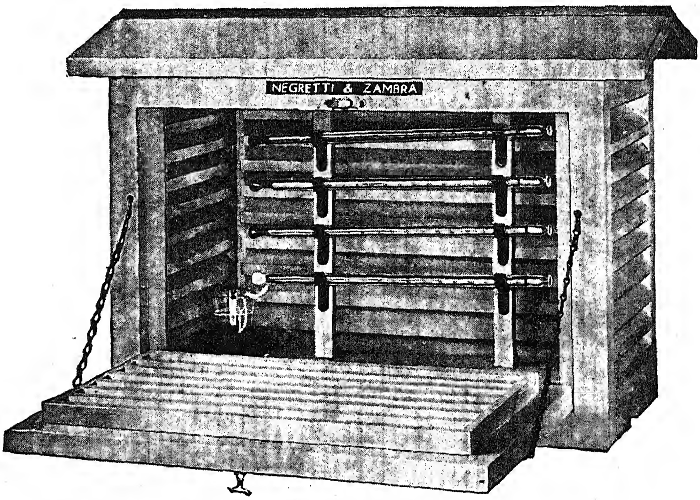

Fig. VI. 1. Stevenson screen (Bilham type), containing dry bulb, wet bulb, maximum and minimum thermometers.

$11\frac{1}{2}$ in. high, 16 in. wide and 7 in. deep, with double louvred sides which allow adequate ventilation but provide a complete screen against direct radiation. A larger version is also made for housing additional recording instruments.

Atmospheric Pressure

The pressure exerted by the atmosphere is one of the most fundamental meteorological parameters. A full account of the

various standard types of mercury and aneroid barometers is given in Chapter XIX of *Scientific Instruments.*

The hypsometer is also occasionally used for making pressure observations, especially on expeditions where mercury barometers would be too fragile and cumbersome and aneroid barometers would not be sufficiently stable. This consists of a boiler from which steam passes into a long double tube containing a very accurate thermometer. Since water boils at different temperatures under different pressures, by reading the temperature and consulting a table, the pressure at which the water is boiling can be found. Adequate precautions must be taken to ensure that the resistance of the tubes does not cause an excess of pressure inside the boiler. In some cases the thermometer is graduated direct in millibars. With the most refined form of hypsometer it is possible to achieve an accuracy of about 0.2 mb. (0.006 inch of mercury) in the pressure reading.

Temperature

Thermometers are used by meteorologists to measure the temperature of the air, the soil and the sea. The general principles of thermometers are dealt with in Chapter XV of *Scientific Instruments.*

Ordinary thermometers are invariably of the mercury-in-glass type, except in places where temperatures below — 39° C., the freezing point of mercury, are experienced, when they are replaced by spirit-in-glass instruments or by mercury-thallium thermometers (freezing point — 60° C.). Maximum thermometers are similar to the ordinary ones, except that the bore is constricted near the bulb to prevent the mercury column from receding as the temperature falls. Spirit-in-glass thermometers are used for recording the minimum temperature. A small glass index in the bore recedes with the spirit as the temperature falls, being acted on by the surface tension of the meniscus, but it remains stationary when the column rises again. Both maximum and minimum thermometers have to be set after taking a reading, the former by shaking the mercury into the bulb and the latter by tipping the thermometer until the index contacts the meniscus.

The sensitive element in most recording thermometers or thermographs is a bimetallic coil, made from a strip of two metals (generally invar and brass) with dissimilar coefficients of expansion. The coil winds and unwinds as the temperature changes and if one end is fixed, a pen attached by a lever to the other end will record the temperature.

Humidity

The amount of water vapour in the atmosphere is expressed in several different ways, the commonest being the relative humidity, i.e. the ratio of the actual water vapour pressure to the saturated

vapour pressure expressed as a percentage, and the dew-point, i.e. the temperature at which the sample of air would be saturated. It should be noted that the relative humidity does not express the actual amount of water vapour present; the temperature must also be stated to give a complete specification. The accurate measurement of humidity is a difficult problem and there is no entirely satisfactory instrument for routine use.

The hygrometer most widely used is the wet and dry bulb thermometer, or "psychrometer". It consists of two thermometers (generally mercury in glass) mounted side by side, one bulb being covered by thin muslin which should be kept continuously wet. As water evaporates from the wet bulb the air immediately in contact with the bulb and the bulb itself are cooled below the dry bulb temperature, the amount of cooling being a function of the rate of evaporation. The complete theory is extremely complex and in practice an empirical formula is always used to convert the wet and dry bulb temperatures into relative humidity. A useful account of the various formulae is given in *Hygrometic Tables* published by H.M.S.O. The main "constant" in the formula is a function of the rate of ventilation but changes very little for rates above 3m./sec. For accurate measurements of humidity it is therefore simplest to ensure that the ventilation is adequate, and the Assmann psychrometer (Fig. VI. 2) is designed to fulfil this need. A clockwork or electric motor drives a fan which draws air past the bulbs in the double-walled anti-radiation tubes.

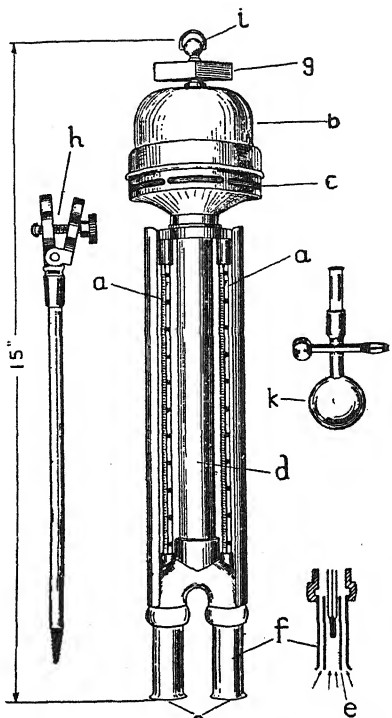

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Fig. VI. 2. Assmann psychrometer.
a — the thermometers.
b — dome containing clockwork.
c — the fan and air outlets.
d — main air duct.
e — air inlets.
f — polished tubes protecting thermometers.
g — key for winding clockwork.
h — clamp for supporting the instrument.
i — the point of support of the instrument. The clamp holds the ball securely but allows the instrument to hang vertically.
k — injector for wetting muslin of wet bulb.

Many hygrometers have been designed on the absorption principle,

using as the sensitive element a hygroscopic substance which changes one or other of its physical properties (e.g. length or electric resistance) as the humidity changes. The oldest is the hair hygrograph, in which the change of length of specially treated human hair operates a pen-arm. The change of length is not linear throughout the whole range of humidity, but in some instruments the record is made linear by a system of cams. As the zero of hair hygrographs is not very stable, they should be checked periodically against an accurate psychrometer. It is interesting that hair is sensitive to relative humidity and not to the absolute amount of water vapour.

The most accurate hygrometer used by meteorologists is the dew-point instrument, and more will be said about this when dealing with aircraft instruments.

Surface Wind Speed and Direction

One of the oldest and most ubiquitous meteorological instrument is the wind vane, which consists basically of a plate free to turn on a vertical axis about which it is unsymmetrical. The side of the plate offering least resistance to the wind will point to the direction from which the wind is coming. The wind direction may be read direct against compass point indicators mounted directly under the wind vane, or the motion of the vane may be transmitted by a variety of methods to a remote indicator or recorder (see Chapter XIX).

The principle of one type of pressure tube anemometer has already been described in Chapter XVII of *Scientific Instruments*. In the Dines anemograph the pressure difference between the pressure and static tubes from a pitot-static head operates a float which is so shaped that a recording pen, attached to the top of the float, gives a linear record of the wind speed.

The simplest anemometer is the pressure plate type, in which the angle to which a plate, free to move about a horizontal axis, is diverted from the vertical, gives a measure of the wind speed. Cup anemometers are, however, much more widely used by meteorologists, the modern form consisting of three hemispherical or conical cups with beaded edges, each cup mounted with its diametral plane vertical at the end of a short arm. The arms are mounted radially on a vertical shaft

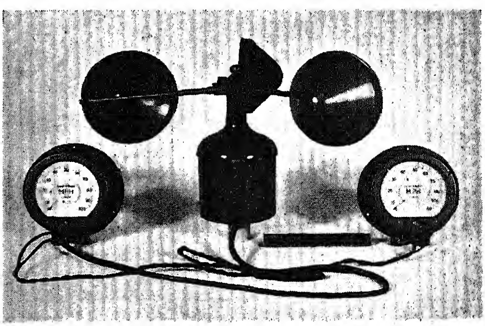

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Fig. VI. 3. Cup generating anemometer.

which is free to rotate, and the rate of rotation of the shaft is an indication of the wind speed. The rate of rotation may be measured by counting the number of complete turns in a given time interval, or may be indicated by a pointer operated on the magnetic drag principle. Alternatively, the output from a small electric generator, operated by the anemometer as shown in Fig. VI. 3, can be transmitted to a remote indicating or recording voltmeter. The generator anemometer has the advantage that it enables one to estimate the gusts of the wind, whereas the counting anemometer only gives the mean wind speed.

Precipitation

Precipitation includes all the water reaching the earth's surface in the form of rain, snow, hail and dew, and is measured in inches or millimetres, i.e. the depth of the precipitation on a flat surface, assuming that there are no losses. Special methods have been devised for measuring dew and the various frozen forms of precipitation, but the only instruments in common use are primarily rain gauges.

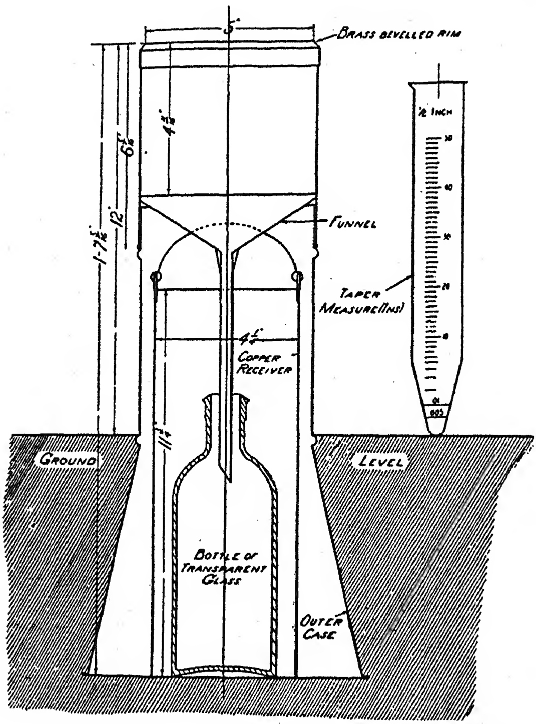

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Fig. VI. 4. Meteorological Office five-inch rain gauge.

The essential part of a rain gauge is the rim of the collector, which must be accurately circular and of known diameter, generally 5 in. or 8 in. in this country. The construction of the Meteorological Office gauge will be quite clear from Fig. VI. 4. A depth of some 4 in. is allowed between the brass bevelled rim and the funnel to minimise losses due to splashing. The rain is collected in the glass bottle and subsequently measured (generally once daily) in an accurately graduated glass measure with a tapered base.

Recording rain gauges are made in a great variety of models, one difficulty being to provide an open scale for light rainfall without rendering the gauge useless in heavy rain. The object of the recording gauges is to indicate the times of beginning and ending of rainfall and the rate of rainfall; accurate observations of the total amount of rainfall are usually made with a standard gauge and measure. They may be divided into three main groups: float-siphon gauges, tipping bucket gauges, and weighing gauges. In the float gauges a float rises in a collecting chamber until the water reaches a certain level, when a siphon comes into operation and the chamber is partially emptied. A pen attached to the top of the float records the movement of the float. In the Dines tilting-siphon rain gauge (Fig. VI. 5) the chamber rests on knife edges. When the float rises to the top of the chamber it lifts a small trigger and the whole chamber tilts over, thereby starting the siphon action in a positive manner. A counterweight brings the chamber back into its normal position when sufficient water has passed out. In the tipping bucket pattern the rain passes into an open bucket divided into two sections and pivoted about its centre. When a certain quantity of water has collected in one section the bucket tips over, and the rain then collects in the other section while the first section is emptied. The record simply marks the number of times the bucket has tipped, each tip generally corresponding to 0.01 in. of rainfall. The advantage of the weighing gauges is that they record snow and hail immediately as well as rain; the precipitation is simply collected in a chamber whose weight is recorded by a balance mechanism.

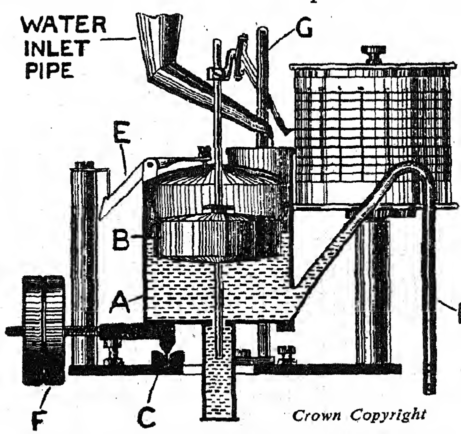

Fig. VI. 5. Dines tilting-siphon rain gauge.
A. Chamber. D. Siphon Tube.
B. Float. E. Trigger.
C. Knife Edge. F. Counter-weight.
G. Rod.

Visibility

Visibility is generally defined as the maximum distance at which objects are visible to an observer under normal illumination. This is a subjective definition involving the quality of the observer's eyesight; the nature of the object and the precise meaning of "normal" illumination are also important. Many attempts have been and are being made to overcome the looseness of this definition by the use of instruments to measure definite physical properties of the atmosphere, suchas the extinction coefficient. The difficulties increase at night when the usual method is to assess the maximum distance at which a light of known candle-power is visible. In the Gold visibility meter a neutral light filter is adjusted until a standard lamp at a known distance is just obscured.

Sunshine

Meteorologists are interested in both the duration and intensity of sunshine, but regular observations of the latter are made at only a few observatories equipped with special radiation instruments.

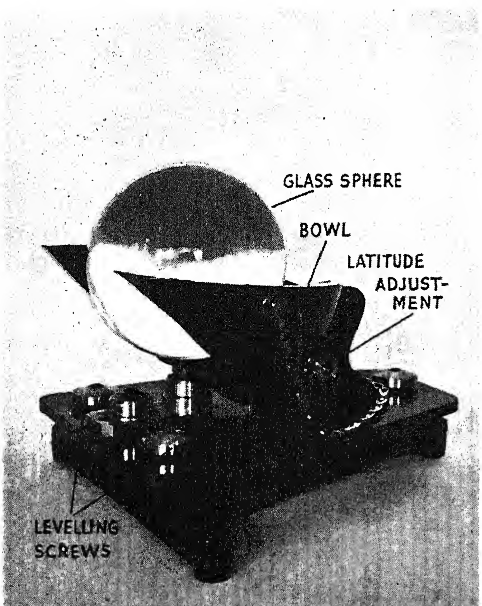

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Fig. VI. 6. Campbell-Stokes sunshine recorder.

The duration of sunshine is generally measured by the Campbell Stokes recorder, illustrated in Fig. VI. 6, in which the rays of the sun are focused by a glass sphere on a special card. If the sun is sufficiently bright, the card will be burned, and the length of the burn will give a direct measure of the duration of the sunshine. The card is held in a bowl which is part of the surface of a sphere concentric with the glass sphere. The instrument should be mounted facing due south and the bowl adjusted in elevation according to the latitude of the station. The chief difficulty with this very simple instrument is to ensure a uniform practice amongst observers in measuring the records so that results from different stations will be comparable. It is also essential that the card should be made to the correct specification.

Cloud Observations

Weather observers are asked to report the amount, form, height and motion of clouds. Of these, the amount and form are generally estimated by eye, the height may be measured (especially at night) by a cloud searchlight or ceiling balloon, and the motion is determined with the aid of a nephoscope. The searchlight projects a narrow beam of light vertically upwards and the elevation of the spot formed on the base of the cloud is measured by an observer, standing 1,000 ft. or more from the searchlight, with the aid of a clinometer or alidade. Knowing the base length, the height of the cloud may be calculated. A nephoscope is basically a series of reference lines against which the direction and the angular rate of motion of the cloud may be measured. If the height of the cloud is known, the actual speed of the cloud can be calculated. The Besson nephoscope, in general use in this country, is illustrated in Fig. VI. 7. Seven equidistant vertical spikes are attached to a horizontal bar which may be rotated about a vertical axis. To make an observation, the observer stands so that the cloud is in line with the central spike. The bar is rotated until the cloud appears to move along the line of spikes. The direction in which the bar is pointing, which can be read from the direction plate, will then be the direction of motion of the cloud. The angular speed of the cloud is measured by timing the apparent movement of the cloud from one spike to the next.

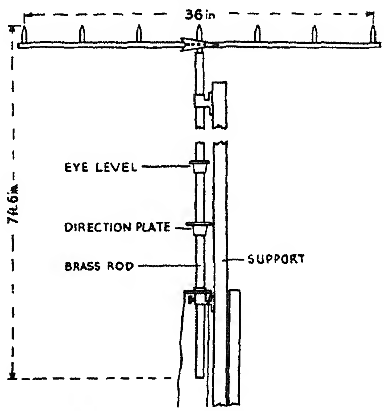

Fig. VI. 7. Besson comb nephoscope.

Upper Winds

The speed and direction of the winds in the upper atmosphere are usually measured by following a pilot balloon as it ascends. In recent years the practice of observing the balloon by radio techniques (see Chapter VII) has become increasingly more popular, but the pilot balloon theodolite is still very widely used. This differs from the surveying theodolite, described in Chapter XXIV of *Scientific Instruments*, chiefly in that it contains a pentagonal prism to bend the light beam at right angles so that the axis of the eyepiece is always horizontal—this is done for convenience in observing the balloon at high angles of elevation. To compute the wind speed from the readings (taken at minute intervals) of azimuth and elevation

at a single station, the height of the balloon must also be estimated. This is done either by assuming a constant rate of ascent or by measuring the angle subtended by a tail attached to the balloon. The computation may be done graphically or with a special slide rule.

Aircraft Instruments

The requirements for aircraft instruments are even more stringent than for ground meteorological instruments in that they have to withstand severe vibration and to cover a wider range while being capable of operation by an observer who may be working at reduced efficiency under the effect of altitude.

The standard barometer is the K.B.B.—Kollsman Aneroid instrument, similar in principle to the altimeter illustrated on p. 198 of *Scientific Instruments* but calibrated in millibars. It has two pointers which make a complete revolution in 1,000 and 100 millibars respectively.

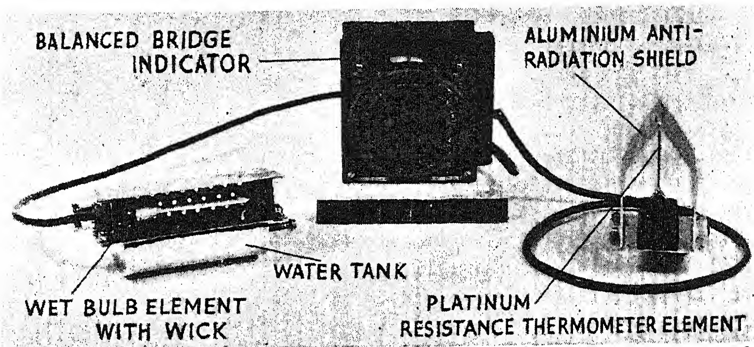

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Fig. VI. 8. Meteorological Office aircraft electrical psychrometer.

For temperature measurement, the earlier spirit-in-glass strut thermometers, designed for mounting on a wing strut of a biplane, are giving place to the electrical resistance thermometer illustrated in Fig. VI. 8. The element consists of a platinum wire wound on a flat mica former, housed in a brass sheath which is pressed flat to exclude air and hence to reduce lag, and surrounded by an anodised aluminium anti-radiation shield. The balanced-bridge indicator is a very compact and robust Wheatstone bridge, the slide wire being mounted round the edge of a circular disc and the sliding contact being operated by a large knob through a 9 : 1 reduction drive.

Humidity is by far the most difficult element to measure from an aircraft on account of the very low quantity of water vapour which corresponds to saturation conditions at low temperatures. Both the

strut thermometer and the electrical resistance thermometer have been adapted for use as psychrometers, but they are virtually useless below — 20° C., where a wet bulb depression of only 1° C. corresponds to a relative humidity of 40%. The Dobson-Brewer frost-point hygrometer shown in Fig. VI. 9 is the most satisfactory aircraft hygrometer yet devised. It operates on the dew-point principle in which a highly polished surface is cooled until a deposit of dew is formed; the mean of the temperatures at which the deposit is just increasing and just decreasing is the dew-point of the air sample. In this case the surface is the end of a black anodised aluminium thimble, round the walls of which, in intimate thermal contact, is wound a platinum resistance thermometer element. The thimble is illuminated by an ingenious elliptical mirror-lamp system, and is observed through a magnifying lens. The thimble is cooled by a jet of petrol cooled by liquid air, or a slush of solid CO_2 and petrol. The temperature is measured with the balanced-bridge indicator mentioned above.

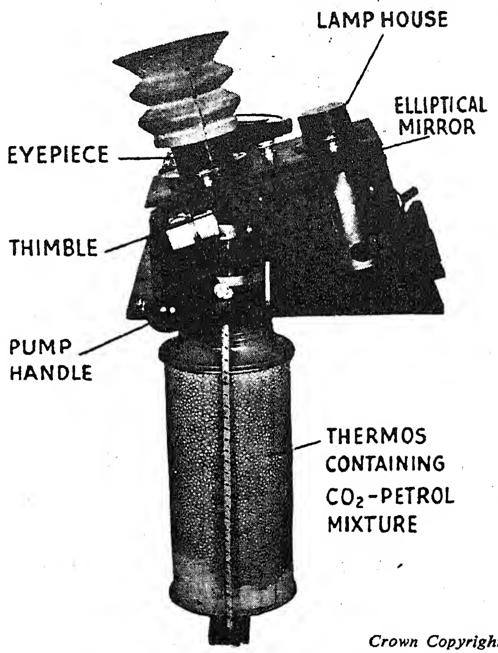

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Fig. VI. 9. Dobson-Brewer frost-point hygrometer.

Marine Instruments

In designing marine instruments it must be remembered that they often have to be used under conditions of strong vibration and violent motion, and that they are generally handled by sailors who are not scientifically trained.

The marine barometer is described on pp. 192-3 of *Scientific Instruments*. For housing the wet and dry bulb thermometers a special light portable form of Stevenson screen is used, as it is desirable to mount the screen to windward. Great care has to be taken to ensure that the water supply for the wet bulb is not contaminated with salt.

The accurate measurement of sea surface temperatures is more difficult than is generally supposed. The usual practice is to collect a sample of sea water in a canvas bucket and to measure its temperature with a thermometer protected by a mahogany frame. Unfortunately the temperature of the water in the bucket may change rapidly when the bucket leaves the sea, due to evaporation and conduction, and there are several other sources of serious errors. A really satisfactory simple instrument has in fact yet to be devised.

Any standard anemometer on board ship will indicate the wind relative to the ship, and the observations will have to be corrected for the ship's motion. The Elliott true wind recorder is an ingenious automatic device for carrying out this correction. The wind speed and direction and the ship's speed and course are fed into the resolver from a cup generating anemometer, magslip wind vane, pitometer log and gyro compass respectively. They are resolved mechanically, and the true wind speed and direction is fed to an indicator or recorder by a magslip system.

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CHAPTER VII

METEOROLOGICAL (ELECTRONIC)

In the past twenty years, radio has become a very important tool to the meteorologist and it is now an indispensable part of his equipment. We are referring here to the application of radio techniques to meteorological instruments—the value of radio telegraphy for the rapid transmission of weather reports and forecasts is quite a separate subject. The chief uses of radio are as a telemetering link in the radio-sonde and as a means of locating a balloon for measuring upper winds, both of which are dealt with below in some detail. Reference is also made to the location of thunderstorms by the study of atmospherics and the detection of storm clouds by radar sets.

Electronic Applications to Meteorology

The most widely used radio meteorological instrument is the radio-sonde, or radio meteorograph, a small radio transmitter which broadcasts information about the meteorological conditions while being carried into the upper atmosphere by a free balloon. In most radio-sondes the transmitted information is confined to the atmospheric pressure and the temperature and relative humidity of the air. The indications of sensitive elements, such as an aneroid box for atmospheric pressure, a bimetallic strip for temperature and a bundle of human hairs for humidity, are converted into some form of variation of the radio signal. An observer on the ground records the radio signals and re-converts them to values of pressure, temperature and humidity with the aid of calibration curves or tables. These curves or tables are obtained by submitting the radio-sonde to varying controlled conditions of pressure, temperature and humidity in test chambers.

The chief considerations in the design of a radio-sonde are accuracy, simplicity, lightness and cheapness. For pressure and temperature an accuracy of 0.5% of the range is needed, while in humidity an accuracy of 3—5% is generally considered satisfactory. As the instrument has to be carried to heights of 60,000 ft. and more, it is essential to keep the weight as low as possible. Although radio-sondes are generally returned to the earth on a parachute, a high percentage are lost, and many of those found are too badly damaged to be used again. They are, therefore, really consumable stores and are used in large numbers—in the British Isles they are now released about four times daily from nine stations—and the need for low cost is most important. With the increasing demands for accurate

weather information for civil aviation, it is estimated that the world consumption of radio-sondes will soon run into several millions per annum.

Radio-sondes may be classified into four groups according to the method used for converting the meteorological information into a variation of the radio signal :

(1) Chronometric radio-sondes, in which the radio signal is interrupted at intervals of time which depend on the meteorological conditions ;

(2) Direct-coding radio-sondes, in which the signals take the form of Morse letters or similar codes ;

(3) and (4) Radio-frequency and audio-frequency radio-sondes, in which the radio-frequency or audio-frequency, respectively, varies with the meteorological conditions.

Chronometric Principle. Chronometric radio-sondes are based on the principle of the Olland cycle, in which the measurement of the distance between a contact operated by the sensitive meteorological element and a fixed contact is converted into a measurement of the time taken by a scanner, driven by clockwork or an electric motor, to pass from one contact to the other. As the meteorological conditions change, the distance between the two contacts increases or decreases, and the time interval measured by the scanner is thus an indication of the value of the meteorological variable.

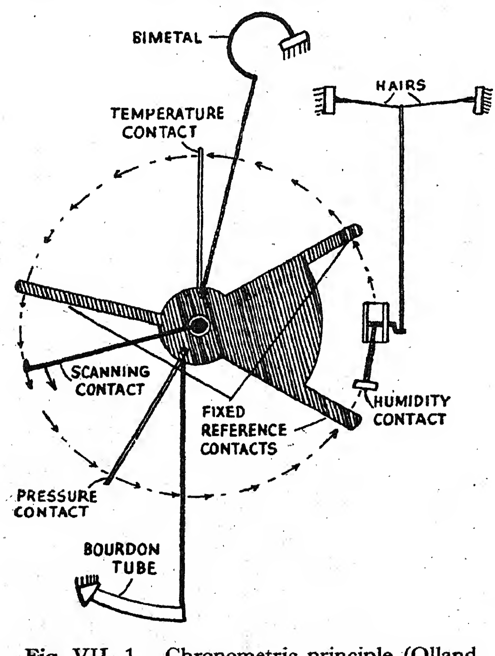

Fig. VII. 1. Chronometric principle (Olland cycle) as shown by Bureau radio-sonde.

The Olland cycle is best illustrated by the French or Bureau radio-sonde, as shown in Fig. VII. 1, in which the scanning contact moves in a circular path and during each revolution makes contact with three fixed reference contacts and three meteorological contacts. The position of the latter in the circular path of the scanner is controlled by the sensitive elements, in this case a Bourdon tube for atmospheric pressure and the customary bimetallic strip and bundle of hairs for air temperature

and relative humidity respectively. Each time a contact is made, the radio transmitter is switched off, and the observations consist simply of measuring the time which elapses between successive breaks in the radio signals.

Variations of the above principle are found in the Canadian radio-sonde, the German Lang and Swiss radio-sondes, and in several earlier American instruments.

The accuracy of chronometric radio-sondes depends on the uniformity of the rate of rotation of the scanner, on the sharpness or abruptness of the contacts and on the accuracy with which the time intervals are measured. The chief advantages over other radio-sonde systems are the reduction of the accuracy to a purely mechanical problem, the ease with which the signals may be automatically recorded on a chronograph and the simplicity of the radio transmitter.

Direct Coding Principle. One of the earliest radio-sondes, developed in Russia by Moltchanoff, transmits the meteorological information as a series of dots and dashes. Contact arms from the meteorological elements travel over a row or "comb" of insulated contacts, which are switched into the main circuit in turn by a complicated commutator system. In the rather neater German army instrument, Morse letters are formed as raised contacts in a series of parallel grooves in a sector wheel which is driven by an electric motor. The meteorological contacts travel along one or other of these grooves as the wheel is driven past.

The advantage of the direct coding principle is that the meteorological values can be interpreted by anyone with a simple radio receiver who can read Morse and is equipped with the appropriate code. On the other hand the accuracy is limited by the unavoidable discontinuity in the readings and by the difficulty in preventing excessive friction when mechanical contacts have to be made for extended periods of time.

Radio-Frequency Variation. Unlike the two systems described above, the variable radio-frequency instruments depend on the conversion of the meteorological indications into electrical quantities, e.g. by connecting the sensitive element to the movable plate of a variable condenser. The condenser is part of the radio-frequency oscillating circuit, so that changes of the meteorological elements are indicated by changes in the radio-frequency, and the ground apparatus is simply a radio-frequency meter. This principle was adopted in the Japanese radio-sonde, in the German navy radio-sonde, and also in the earlier Finnish or Vaisala instrument. In the latter there are altogether five condensers which are switched into the radio-frequency circuit in turn by a switch operated by a three-cup windmill or anemometer, driven by the relative vertical movement of the air past the radio-sonde as it ascends. Two of the condensers are fixed and provide reference points, by which allowance may be made for other

factors which affect the radio-frequency. The remaining three condensers are variable, with the movable plate connected to an aneroid barometer, a bimetallic thermometer and a hair hygrometer respectively. The signal therefore consists of a sequence of five different radio frequencies, the two reference frequencies and one each for pressure, temperature and humidity. The sequence is repeated two or three times a minute, depending on the rate of rotation of the windmill, i.e. on the rate of ascent of the balloon.

One objection to this type of transmitter is that a relatively wide band of radio frequencies is required with consequent danger of interference from other radio stations.

Audio-Frequency Variation. An alternative to varying the radio-frequency is to connect the variable electrical components, operated by the meteorological elements, in the audio-frequency circuit of a simple modulated transmitter. Both the standard American and British radio-sondes work on this principle, which gains the advantage of only using a single radio-frequency at the expense of having a more complicated radio circuit. Although the system does not lend itself so readily to recording as the chronometric type, the Americans have produced a fully automatic recorder for use with their radio-sondes.

In the American instrument the temperature and humidity elements are both variable resistors which are switched, in turn, into the audio-frequency circuit by a switch operated by the pressure element. Errors due to changes of audio-frequency produced by changes of the other electrical components are eliminated by occasionally switching in two reference resistances. The switch consists of eighty conducting strips separated by narrow strips of an insulating material. When the pressure-operated contact is on an insulating strip, the temperature signal is transmitted, and when it is on one of the conducting strips, either the humidity or the reference frequency is sent out. The pressure element, a pair of aneroid capsules, is calibrated, and the pressure at the instant of each change of the switch is known. The temperature element is a glass tube, containing an electrolyte with a large negative temperature coefficient of resistance, with electrodes sealed in at each end; more recently, it has been replaced by a ceramic semi-conductor. The humidity is indicated by the variation of resistance across a strip of material impregnated with a hygroscopic salt such as lithium chloride.

British Radio-Sonde. In the Meteorological Office radio-sonde (see Figs. VII. 2 and VII. 3) the changes in audio-frequency are produced by varying the inductance in the circuit. In each of the three meteorological units the sensitive element is connected to a mumetal armature mounted across the end of a two-coiled inductance. As the element changes, the air gap between the armature and the coils is altered, and this, in turn, changes the value of the inductance.

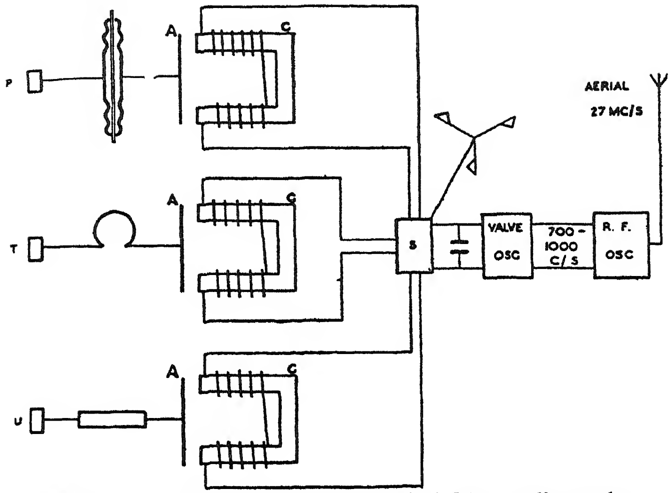

Fig. VII. 2. Principle of Meteorological Office radio-sonde.
A. Mumetal armatures. S. Windmill operated switch.
C. Inductance coils. T. Bimetal strip.
P. Aneroid capsule. U. Gold-beater's skin strip.

The range of frequency is between 700 and 1,000 c/s. A mechanical switch, operated by a three-cup windmill (as in the Finnish radio-sonde), connects the three inductance units in turn into the main circuit, the duration of each contact being 5 or 6 seconds at the normal rate of ascent of 6 metres per second. The circuit consists of the inductance-capacity audio-frequency oscillator connected to a conventional 27 Mc/s Hartley oscillator through a third valve which acts as a buffer in helping to keep the load on the audio-frequency stage constant. The circuit is designed to reduce to a minimum undesirable changes of the audio-frequency; in particular the main condenser has a very low temperature coefficient of capacity.

The pressure element is a single steel aneroid capsule with a very low hysteresis—the maximum width of the hysteresis loop for a 1,000 millibar pressure cycle is only 2 mb. The bimetallic thermometer element is highly polished, and is surrounded by a double walled aluminium shield to minimise radiation errors. It has a rapid speed of response, a very important point for a radio-sonde element, e.g. the bimetal would indicate 50% of a sudden change of temperature in less than 5 seconds in an air stream of 5 m/sec. at normal atmospheric pressure. The sensitive humidity element is a strip of gold-beater's skin, chosen, rather than hair, because of its greater sensitivity and more rapid response to humidity changes especially at low temperatures.

Each meteorological element with its inductance coil forms a separate unit which can be detached from the main body of the

transmitter for calibration and packing. The various radio components are mounted on a circular panel and are housed, together with the battery, in a cylindrical case made of plastic or bakelised cardboard. The complete radio-sonde, as shown in Fig. VII. 4,

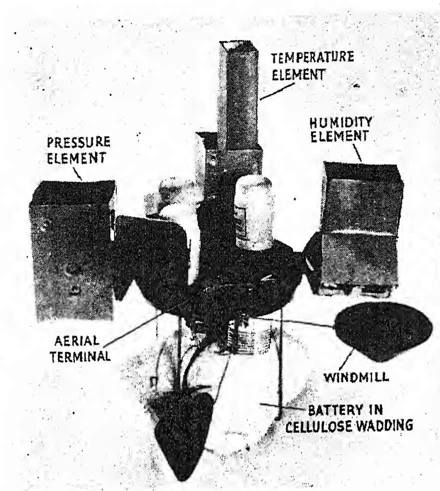

Fig. VII. 3. Meteorological Office radio-sonde (cover removed).

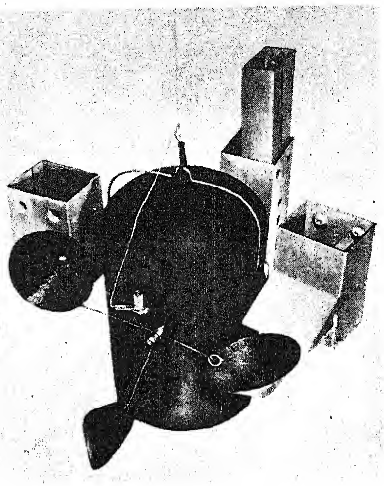

Fig. VII. 4. Meteorological Office radio-sonde ready for ascent.

weighs about 1,350 gm., of which the battery accounts for 350 gm.

The ground equipment consists of a sensitive radio receiver covering the 27-30 Mc/s band, a special Muirhead resistance-capacity oscillator with manual tuning over the 700—1,000 c/s range, and a cathode ray oscillograph. The audio-frequency outputs from the receiver and oscillator are fed to the two pairs of plates in the oscillograph. The frequency of the oscillator is adjusted until the resulting picture on the oscillograph screen is a stationary loop, when its frequency will be equal to the radio-sonde audio-frequency.

Accessories. In addition to the radio-sonde transmitter as described above, a complete radio-sonde assembly includes a balloon, a battery, and in most cases a parachute. Accessories used on the ground include hydrogen cylinders or generators, balloon filling gear, a screen for taking control observations prior to the launch, a radio receiver and associated equipment, standard meteorological instruments, an accurate stop-watch or clock, and in windy localities a special device for launching the balloon in strong winds.

The balloons weigh between 350 and 1,000 gm., and are generally made from natural rubber latex by the Kaysam process which produces balloons of very uniform thickness. At the launch their diameter is about 2 m., and they expand to a diameter of some 5 m.

before bursting at heights of upwards of 15 km. Radio-sonde batteries are designed to be as light as possible, to perform satisfactorily at low temperatures, and to produce the full power required for one to two hours ; they may be either wet or dry. The British type is a bank of primary cells with lead peroxide positive and amalgamated zinc negative plates, and sulphuric acid as the electrolyte. It develops 86 volts H.T. and 2.4 volts L.T. with capacities of 12 and 300 milliampere hours respectively. The battery case is moulded in cellulose acetate, and it is wrapped in several layers of cellulose wadding, as illustrated in Fig. VII. 3, to provide thermal insulation and absorb any acid which is spilled at the launch.

Hydrogen is invariably obtained from cylinders, except in isolated places where transport costs are prohibitive. Special high-pressure generators have been made for such places, using the aluminium-caustic soda or the silicol processes.

The control screen (Fig. VII. 5) is important for obtaining last minute observations from which zero corrections may be applied to the calibration curves. It serves the same function as the Stevenson screen (see Chapter VI), but also provides a rate of ventilation comparable with the normal rate of ascent of the balloon, 5 to 6 metres per second. The screen consists of a double walled chamber in which the radio-sonde can be freely exposed to the air while being completely protected from solar radiation. An electric fan draws air through the chamber, thereby ensuring adequate aspiration of the meteorological elements and causing the windmill to rotate. Accurate measurements of the air temperature and relative humidity are made with an Assmann psychrometer (see p. 74).

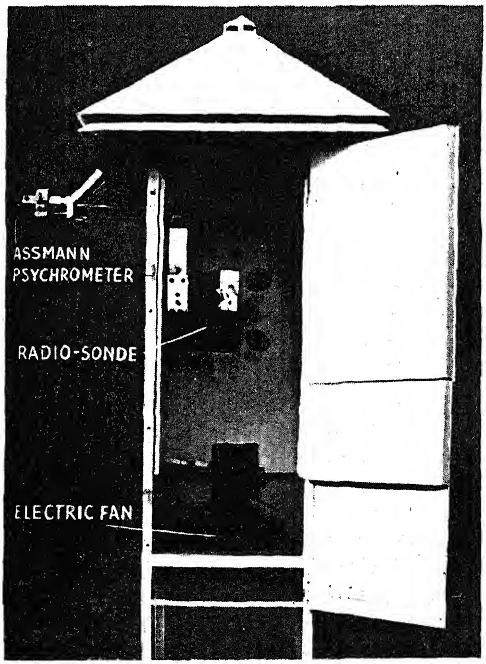

Fig. VII. 5. Radio-sonde control screen.

Calibration. To achieve the high degree of accuracy called for by the meteorologist, it is essential with most types of radio-sonde to calibrate each instrument

individually throughout the whole range of pressure, temperature and humidity. The only serious attempt to avoid this costly procedure is the American temperature element, for which it is claimed that the manufacturing tolerances are sufficiently fine or close to permit the use of standard calibration curves. It is a great convenience for calibration if, as in the British radio-sonde, the elements are detachable; in this case it is also desirable that the calibration should be independent of the remainder of the transmitter, and it is here that the chronometric and direct coding types have the advantage.

Most radio-sonde calibration is done by manual control of pressure, temperature and humidity chambers, and eye readings of the various instruments with subsequent plotting of calibration curves or preparation of tables. There is obviously great scope for the introduction of automatically controlled gear and automatic recording arrangements. Expensive development and installation costs would be justified by the subsequent saving in labour.

The Measurement of Upper Winds by Radio

We have seen above how radio is used to signal information about pressure, temperature and humidity conditions in the upper atmosphere. From such observations at adjacent radio-sonde stations it is possible to calculate the theoretical value of the upper winds, but actual observations of the wind are much more reliable.

The earlier optical methods of measuring the winds in the upper atmosphere, described on p. 79, are rapidly giving way to radio techniques, largely because the latter are not limited to heights below cloud level. The underlying principle of all the methods is to locate in space at regular time intervals a balloon which is drifting freely with the wind as it ascends. This may be done by several different ways, depending on which of the components, azimuth, elevation, height and slant ranges are measured.

D/F Methods. The first method involves the measurement of the azimuth of a balloon borne radio transmitter from two, or preferably three, ground stations 30 km. or more apart. By plotting the azimuths on a chart, the plan position of the balloon is estimated at minute intervals, and the wind speed and direction are read off after judicious smoothing. The corresponding heights are obtained from the simultaneous radio-sonde pressure and temperature measurements.

The Meteorological Office radio direction finder, designed specially for this work at the National Physical Laboratory, is illustrated in Fig. VII. 6. An Adcock H aerial system is connected by shielded transmission lines to a frequency changer unit mounted on an accurate rotor. The frequency changer is connected to the combined intermediate and audio-frequency unit standing on the floor of the hut through a slip ring unit. The audio-frequency output is passed up

through another set of slip rings to a pair of headphones. The aerials are rotated until the position of minimum signal is found when the bearing of the transmitter can be read to the nearest 0.1° off a circular scale. The chief difficulties of this method are in finding suitable sites (for accurate results the requirements are very stringent) and in maintaining three separate stations. With good sites it is possible to estimate the upper winds to a height of 15 km., with a probable error of about 5 km./hr.

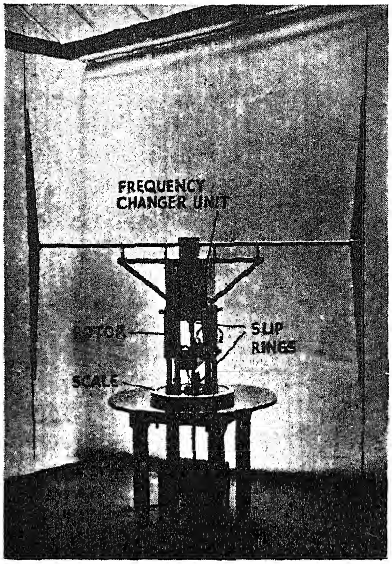

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Fig. VII. 6. Meteorological Office radio direction finder.

Radio Theodolite Methods. To centralise all the observations at one station, attempts have been made to design an accurate "radio theodolite," i.e. a radio direction finding set to measure both azimuth and elevation. To eliminate gross errors in elevation readings it is necessary to use a very high radio-frequency transmitter, 400 Mc/s or higher, but even so it is extremely difficult to obtain adequate accuracy at low elevations and no really satisfactory set is yet in general use.

Radar Methods. The accuracy required in the readings of elevation, especially at low elevations, can be relaxed if it is possible to measure the slant range. This is usually done by attaching a radar reflector to the balloon and following it by one of the accurate modern radar sets. The Army A.A. radar set No. 2, Mk. III, more generally known as the G.L. III, is widely used by the Meteorological Office. The transmitting and receiving dipoles are mounted in the focal planes of separate paraboloids which can be rotated together about horizontal and vertical axes. The aerial system is adjusted until a maximum signal is received back from the target, the signal strength being estimated by watching a set of cathode ray tubes. The slant range can be estimated to the nearest 10 metres between limits of 500 and 60,000 metres, and the azimuth and elevation can each be read to 0.1° throughout the complete ranges of 0°—360° and 0°—90° respectively. The resulting accuracy in wind measurement is ± 3 km./hr., except at extreme range and low elevation. The target is a "corner" reflector, consisting of three mutually perpendicular planes of metallised paper supported by a light wooden framework.

The chief limitations of radar sets at the moment are the high initial expense, the need for expert maintenance and the relatively low maximum range, which with a mean wind of 100 km./hr. limits the observations to a height of 10 km. at the usual balloon rates of ascent.

Responder Systems. An alternative method of obtaining slant range is to replace the passive reflector of the radar system by a radio responder, which receives the signals from a ground transmitter and re-radiates them, generally on a different radio-frequency. By this method it is possible to measure much greater ranges than by the normal radar system, but it involves a more complicated and expensive airborne unit. Successful responder radio-sondes were brought into use in both Switzerland and Germany during the recent war. If the airborne unit is developed into a form in which it can be cheaply mass produced, this may well be the most widely used form of radio wind measurement in the future.

Automatic Weather Stations

So far we have seen how radio is providing the meteorologist with valuable information about the upper atmosphere. We will now show how it can be used for transmitting information about conditions on the ground. The function of an automatic weather station is to report the weather conditions at a given place by radio without the presence of a human observer. They are designed for use in remote places, such as in mountainous regions, in the middle of deserts or oceans, or in the polar regions. Ideally, they should transmit the meteorological information at regular intervals throughout the day without attention for 6 or 12 months, but this has not so far been achieved on a routine basis. Automatic stations are now being developed in Russia and have been used from time to time by the Americans, Canadians and Germans.

Basically the problem of converting the meteorological data into radio signals is the same as in the radio-sondes, but the practical problems are very different. The chief difficulties are to ensure absolute reliability for such long periods without attention, to provide power for the radio transmitter, to develop a sufficiently accurate clock and to design a housing for the sensitive elements which will allow sufficient ventilation and yet not be liable to be choked by snow or sand. Mooring is an additional problem for the ocean stations, not to mention the prevention of corrosion in the presence of salt air. Stations have been designed to transmit surface pressure, temperature and humidity, wind strength and direction, sea temperature and even duration of sunshine and amount of precipitation. One important element which is so far lacking is the cloud type and amount; no doubt this could be added by a television system.

Radar Storm Location

When centimetric radar sets were brought into routine use for detecting aircraft, it was found that echoes were received from storm clouds. These were regarded as largely of nuisance value at first, until it was realized that this new method of locating heavy clouds had practical applications. The strongest echoes are obtained from clouds which are liable to be dangerous for aircraft, and a radar set which can warn a pilot of the presence of such clouds at a distance of up to 50 miles is therefore a valuable safety instrument. Depending on the type of presentation given by the radar set, it is possible to estimate both the horizontal extent of the cloud and its vertical development. The investigation of these echoes is still in its early stages, but it seems probable that radar will eventually provide the meteorologist with much useful information about the structure of clouds and will be widely used both for meteorological research and for the safe navigation of aircraft round dangerous clouds.

Location of Atmospherics

One of the oldest applications of radio by the meteorologist is the location of the source of atmospherics, those short bursts of noise which are heard when listening to broadcasting stations, especially on the longer wavelengths. Atmospherics are associated with the meteorological conditions and are most frequent in thunderstorms and regions of frontal activity. The possibility of locating distant thunderstorms by measuring the bearing of arrival of atmospherics at two or more stations has been investigated since 1915 in this country, France, Germany, Switzerland and America. From the regular observations now made at four stations in the British Isles, it is possible to locate areas of thunderstorm activity up to 1,000 miles away—much further, but with less detail than by radar techniques.

The instrument now used to measure the direction of the atmospherics is called a cathode ray direction finder. It consists of two pairs of fixed loop aerials mounted at right angles and connected through separate amplifiers to the two pairs of plates of a cathode ray tube in such a way that the orientation of the line produced on the tube by an atmospheric signal indicates the direction of arrival of the signal. The picture on the tube persists long enough to enable an observer to read the bearing of the atmospheric. Simultaneous bearings from the different stations are plotted on a chart at a central station, and from their intersections it is possible to estimate the location of the source of the atmospheric.

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CHAPTER VIII

NAVIGATIONAL

Although the general problem is the same, air and sea navigation differ considerably in technique. The former is in many ways more difficult and calls for special instruments. The effect of wind, tides and ocean currents on a ship is relatively small, except over long periods, but an aircraft moves bodily with the air mass which supports it, with the result that to its measured air speed must be added the whole of that variable speed vector, the wind velocity. At an altitude of 20,000 ft. winds of 100 miles an hour are not uncommon even in clear weather—in some parts of the world winds of as much as 200 m.p.h. have been encountered—so it is not surprising that wind measurement figures largely among the problems which face the air navigator.

A special difficulty is the short time available to the air navigator for working and plotting on account of the high speeds involved. During even the simplest computation his aircraft may move several miles. A good air navigator can, for example, take a sextant observation in from two to three minutes and compute his position line in about the same time, but during this interval his aircraft may have travelled some twenty miles. Thus the navigator must spend most of his time identifying a point some miles back on his track and deducing from it the time when he will reach a point some miles ahead. He rarely lives in the present. To make matters worse his computations must sometimes be done under the most appalling working conditions, especially in war-time, at high altitudes under oxygen for example, or in extremes of cold.

The navigator must, therefore, be relieved of as much work as possible. He is provided with special computors and, as far as possible, with automatic instruments. Of the latter, the basic system is the automatic dead-reckoning system.

Automatic Dead-Reckoning Instruments

The function of the automatic dead-reckoning system of instruments is to maintain by mechanical means a continuous record of the position of the aircraft by reference to the directions and distances of its movements from its starting point. Direction is taken from the distant-reading gyro-magnetic compass. Distance, relative to the air mass, is obtained from a device known as the air-mileage unit, an analogue of the ship's log. The output from these two is combined automatically, to record change of position, in an instrument called the air position indicator. This gives position relative to the air mass

and the movements of the air mass (that is, the effect of the wind vector) are added in another device which thus displays the true or ground position. This instrument is therefore called the ground position indicator. The exact function of these instruments will be clearer if we briefly describe each of them in turn.

The Distant-Reading Gyro-Magnetic Compass

A ship's gyro-compass cannot be used in the air, not only because of its weight but also on account of the high speed of aircraft. Such a compass derives its directional properties from the change in the absolute direction of the earth's gravitational pull when the earth and gyro are rotating together. At high latitudes, however, an aircraft may be moving round the earth at the same speed as, but in the opposite direction to, the earth's rotation. In this event there is no overall angular movement and therefore no directional effect. Thus the best that can be expected in the air is the directional rigidity of the free gyroscope, and this is limited by friction and constructional errors, with the result that a 'wander' of about 8° an hour may be expected from a small airborne gyro.

The obvious alternative, a magnetic compass, develops serious errors, particularly during turns, because the vertical component of the earth's field deflects the needle unless the card is maintained accurately horizontal. The modern aircraft compass therefore embodies a magnetic compass detector which corrects the wander of a free horizontal axis gyroscope. This correction is so slow in action that the transitory errors of the magnetic detector are smoothed out.

Modern magnetic detectors usually employ the so-called Fluxgate or Fluxvalve principle. A crude explanation of this is as follows: If a bar or core of very soft iron is periodically saturated by a surrounding coil carrying alternating current the earth's field can only induce lines of force in it when the current falls to zero. The earth's field is, in effect, let in and pushed out of the core at twice the excitation frequency; thus a double frequency

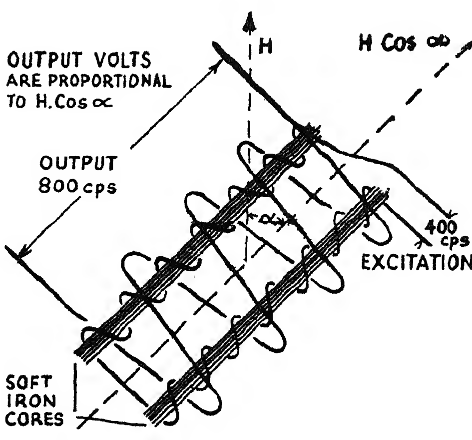

Fig. VIII. 1. Principle of the 'Fluxgate' magentic detector.

voltage is induced in any surrounding coil proportional to the component of the earth's field along the core. Two parallel cores are generally employed, excited by coils wound in opposite directions. The double frequency induction, which is in the same direction for both cores, can then be picked up from a coil surrounding both cores, the fields due to the excitation cancelling one another out. (Fig. VIII. 1.)

The complete detector generally consists of two or more pairs of cores symmetrically disposed and pendulously mounted to keep them in a horizontal plane. Since the detector is small and contains no moving parts, it can be mounted in the wing-tip of the aircraft, away from interfering magnetic fields. The voltages from these pairs of cores are fed to an autosyn unit, that is, to a corresponding system of coils wound on a soft iron stator, where they set up across the stator an alternating magnetic field, the direction of which corresponds with the direction of the earth's field at the detector. Inside the stator is a small rotor coil which is coupled to the vertical-axis gimbal of the free gyroscope. The rotor picks up a voltage from

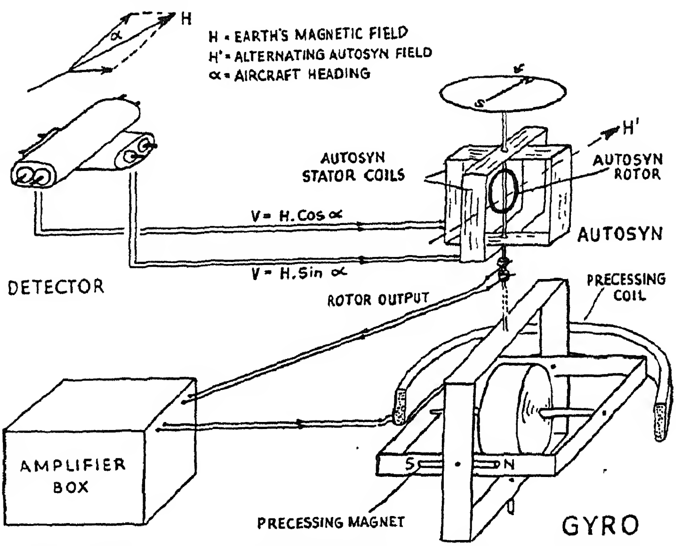

Fig. VIII. 2. Schematic diagram of a modern gyro-magnetic compass.

the alternating magnetic field except when its axis is at right-angles to the field. This voltage is amplified, rectified, and applied to two vertical coils round the gyroscope. The magnetic field from the current in these coils exerts a torque on small permanent magnets attached to the horizontal gimbal of the gyroscope, thus precessing

the gyro and with it the rotor. The direction of the current in the precessing coils is so arranged that the rotor is always turned until it lies at right-angles to the field set up in the stator. Any wander of the gyro and rotor from this position thus produces a steady restraining torque. The maximum precession rate is too small for short-lived changes in the direction of the signal from the detector to have any effect. The gyro carries a dial and is mounted in the instrument panel before the pilot.

In some instruments the stator-rotor system is not mounted in the same case as the gyro, but is mounted in a navigator's repeater and made to follow the gyro by electrical transmission. This enables the navigator to correct the instrument for magnetic variation by rotating the stator so that the whole instrument can indicate true, rather than magnetic, north. On the same shaft as the rotor a transmitter is mounted which repeats electrically the directional indications to other compass dials or to instruments such as the air position indicator. (Figs. VIII. 2 and 3.)

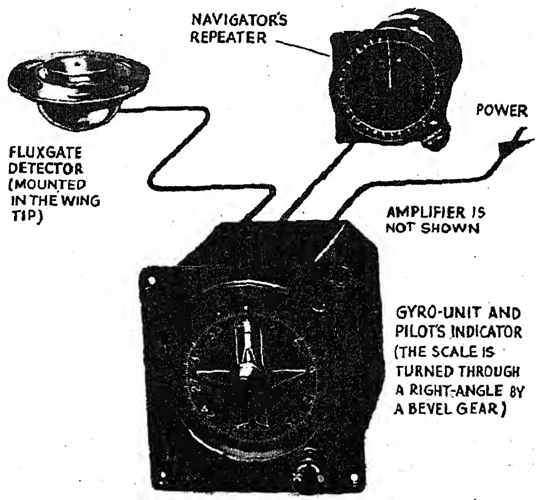

Fig. VIII. 3. The Sperry gyro-magnetic compass.

The Air Mileage Unit

This instrument calculates the speed of the aircraft, relative to the air mass that supports it, by means of the dynamic pressure generated at the pitot tube of the aircraft, translating it into a shaft rotation proportional to this speed. The number of rotations of such a shaft is therefore proportional to the distance travelled.

If a tube—called the pitot tube—which is open at one end, is mounted outside the disturbed region of the slipstream of the aircraft,

with its axis along the line of flight and the open end forward, a dynamic or pitot pressure is built up inside it by the air speed which is equal to $\frac{1}{2}dv^2$, where v is the aircraft speed and d the density of the air. (This is an approximation but is adequate for low air speeds.)

The air mileage unit conducts a kind of wind tunnel experiment. Air at the outside temperature and pressure is whirled round by a paddle-wheel fan and is directed against a small internal pitot tube. The pressure from this is balanced against the external pitot pressure. In these circumstances, since the air in the fan moves with the paddle blades, it is not difficult to see that the speed of rotation of the paddle (the inside air speed) will be directly related to the outside air speed.

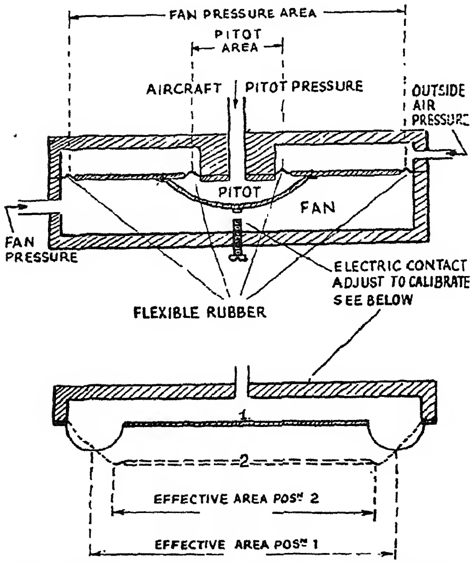

Fig. VIII. 4. The Air Mileage Unit diaphragm system and calibration.

The balance of the fan and aircraft pitot pressures is obtained by applying them one to each side of a flabby diaphragm system, the movement of which is made to control the fan speed. This diaphragm system, which is illustrated diagrammatically in Fig. VIII. 4, is so arranged that the fan pressure is applied over a much bigger area than the pitot pressure, so that the diaphragm system is balanced when the fan pressure is a given fraction of the pitot pressure. The fan then need not be run so fast. For a convenient range of fan speeds a ratio of diaphragm areas of as much as 8 or 10 to one is desirable, even though the fan is twice as efficient in generating pitot pressure as the aircraft. This added efficiency comes from the centrifugal force in the fan, which by compressing the air against the circumferential wall of the fan casing actually doubles the pitot pressure generated. Thus, if the diaphragm is in its balanced or rest position the pressure relationship is :

$$dw^2 = \tfrac{1}{2}kdv^2 \quad \text{whence} \quad w = \sqrt{\tfrac{1}{2}k}.v$$

where w is the fan speed, k the ratio of diaphragm areas, v the air speed, and d the air density.

The control of the fan speed is simple. The electric motor driving the fan accelerates until the fan pressure exceeds the aircraft pressure, when the diaphragm is pushed across and makes a contact which, through a relay, inserts a resistance into the field winding of the motor. This slows it down and the fan pressure drops until the contact is re-made. The motor, therefore, runs at a speed which wavers slightly about the desired value.

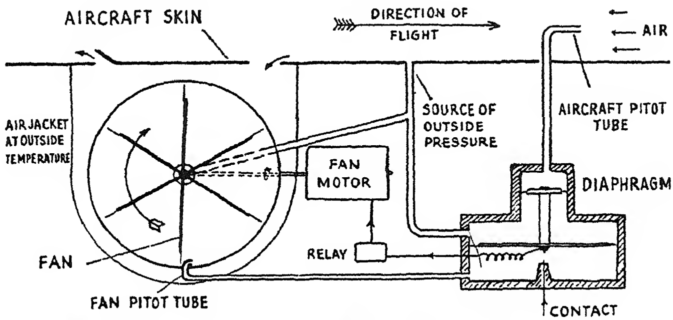

Fig. VIII. 5. Schematic diagram of the Air Mileage Unit.

Fig. VIII. 5 is a schematic diagram of the instrument, of which an interesting feature is the neat way in which it is calibrated. This is done by screwing in or out the screw carrying the diaphragm contact. The effective area of the diaphragm alters as it moves, so that by adjusting the point at which contact is made the calibration constant k is adjusted. (Fig. VIII. 4.)

The distance output from the air mileage unit is usually taken from a flexible shaft connected to the fan motor through a reduction gear.

The Air Position Indicator

The air position indicator combines the outputs of the compass and of the air mileage unit. The flexible shaft from the latter drives two infinitely variable friction gears which are adjusted by a repeater motor from the compass so as to reduce the input speeds according to the sine and cosine of the heading of the aircraft. The output speeds from these gears then represent, the one mileage travelled east and west, the other mileage north or south.

In the simplest form of instrument these two output rotations are fed to counters of the cyclometer type reading in miles N.-S. and E.-W. of base. In the instruments carried in long range aircraft the output is transformed into latitude and longitude. Since sixty nautical miles N.-S. always represents one degree change of latitude, the N.-S. output only has to be fed to a counter in angular measure instead of in miles.

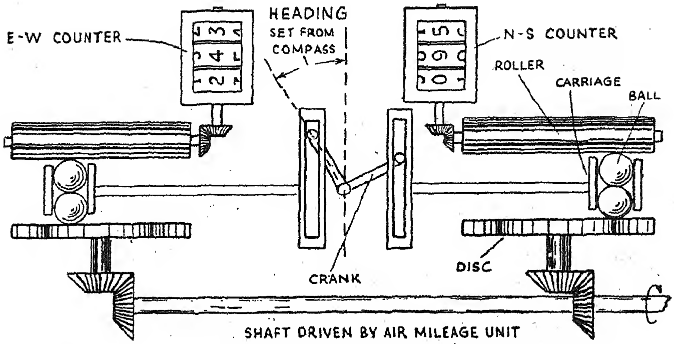

Fig. VIII. 6. The principle of the Air Position Indicator.

The E.-W. mileage is not so simple, it has to be increased according to a secant law as one leaves the Equator because the meridians converge towards the pole, and the nautical mile therefore represents an increasing change in longitude as one goes north. The E.-W. mileage is increased by a third infinitely variable friction gear whose speed gain is adjusted from the latitude output. The output from this third "secant" gear is fed to a counter in angular measure reading in longitude. If the two sets of counters are set to the latitude and longitude of the starting point, they continue to record the air position of the aircraft during the flight.

The infinitely variable gears used are of the disc, ball and roller type. The input shaft turns a flat, hardened and ground steel disc. On this is pressed a steel ball which fits in a carriage running diametrically across the disc. The movements of this ball are transmitted to a hardened and ground steel roller, whose axis is parallel to the

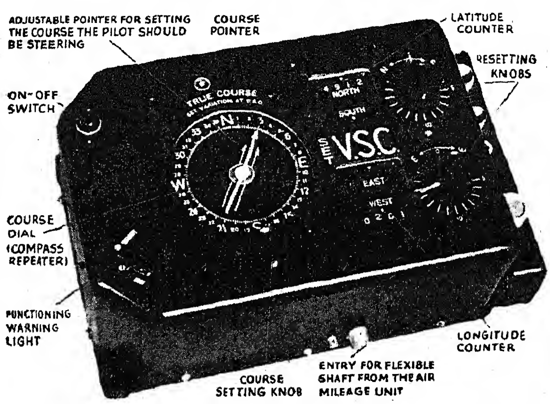

Fig. VIII. 7. An Air Position Indicator.

carriage, through a second steel ball mounted above the first in the same carriage. The roller, which is spring-loaded on to the balls and through them on to the disc, provides the output drive. The two balls are required in order that the carriage may move smoothly—a single ball would be forced to slip, as the carriage was moved, either at the disc or at the roller. Considerable care is required in the manufacture of these gears since they must be free from slip and must give an error of transmission of not more than 1 per cent. A schematic diagram of the instrument is shown in Fig. VIII. 6.

The Ground Position Indicator

To find his true or ground position from the air position indicator, the navigator must plot the air position on a chart and lay off a line from it in the direction of the wind. The ground position lies along this line at a distance equal to the product of the wind speed and the time it has been blowing. Ground position indicators eliminate this plotting, adding the wind effect automatically so as to indicate ground position direct. They contain small motors, governed to run at a constant speed, which drive two friction gears as in the air position indicator. These gears are adjusted manually by the navigator so that the speeds of their output shafts are proportional to the north-south and east-west components of the wind. The output rotations are then added to the shaft rotations of the air position indicator (which are repeated to the instrument electrically) by differential gears, with the result that the overall motions represent miles travelled across the ground north-south and east-west.

Two forms of ground position indicator exist; a small one in which the positional information is presented on counters and a larger one in which the output shafts drive screws which move tangent arms so as to shift a small optical projection system. This throws a small spot of light representing the aircraft's position upon a chart mounted just below the instrument. The spot thus indicates the position of the aircraft at any moment.

In addition to the mechanical devices described above, electrical systems have been devised such as one in which a voltage generated by the speed measuring instrument is resolved by a potentiometer following the sine law into voltages N.-S. and E.-W. These voltages are augmented with manually adjusted voltages representing the components of wind and the overall voltages are applied to two small integrating or "metering" motors running at a speed accurately proportional to the applied voltage. The drive from these is connected to counters as before.

The field of development of such instruments is by no means fully explored. Ultimately we shall probably have instruments which, beside telling the navigator where he is, eliminate all computation by indicating to him automatically his course to, and distance from,

his objective. The limitations are, of course, cost and complexity; also the restricted space available for such devices in modern aircraft.

Wind-Finding Instruments

In describing the ground position indicator, we mentioned that the wind vector was set manually upon it by the navigator. This wind vector may be a meteorological forecast in the first place, but such a prediction must be checked and amended continuously throughout the flight. We come, then, to the instruments for doing this.

Drift Sights

If it is not possible to fix the aircraft's track exactly by identifying the points over which it passes, the simplest way of checking its track is to use a drift sight. This instrument determines by visual observation the angle between the aircraft heading and its direction of movement over the ground. Two such measurements on different headings enable the wind to be calculated.

There are two types of drift sight, the vertical type and the tail drift sight. In the vertical variety the navigator looks straight down at the ground through an optical system with a fixed field of view, watching the passage of objects on the ground across it. In the tail sight the navigator follows a selected object over which the aircraft has passed (or, if at sea, a marker dropped from the aircraft on to the water) in an optical sight whose field of view can be swung round and rotated backwards. By keeping an object in the centre of this field he can measure the direction in which it falls astern, that is, his own track in reverse.

The Drift Recorder is a typical modern vertical drift sight. It consists of a short tube containing opposed mirrors which projects through the side of the aircraft, giving the navigator a view downwards and slightly outwards so as to clear the bulge of the fuselage. A lens system in this tube forms an image of the ground in a plane which very nearly coincides with the flat upper surface of the innermost lens. This lens is rotatable and is engraved with a number of parallel lines. The engraved upper surface is viewed through an eyepiece, the image of the ground and the parallel lines being seen superimposed. If the engraved lens is turned until the objects on the ground appear to move down the parallel lines, the drift is the angle between these lines and the fore-and-aft axis of the aircraft, in other words the angle through which the lens has been rotated from the straight.

Vertical drift sights are particularly liable to errors due to the roll of the aircraft. When the craft rolls, the field of view moves across the ground, producing an apparent velocity in the beam direction which is indistinguishable from, and therefore compounded

with, the aircraft's own velocity, thus giving an erroneous drift. To eliminate this, the drift recorder has a small needle with a dot on the end which slides over the top of the engraved lens in the image plane. This needle is coupled to a pencil by a pantograph linkage so that, if the dot is made to follow the movement of an object on the ground the pencil makes an enlarged trace of its movements on a ground glass plate beneath which is a rotatable disc engraved with parallel lines like the graticule lens. If the aircraft were steady, the pencil trace would be straight. Roll errors, since their duration is short compared with the time of passage of objects across the field of view (except at low altitudes), produce random humps and hollows in the trace, but the engraved disc can be aligned with the mean direction of the trace and a reasonable estimate of the drift thus obtained.

An alternative but more complicated way of eliminating roll errors is to stabilise the graticule of parallel lines with a gyroscope so that they follow the ground rather than the field of view when the aircraft banks. This is done by mounting the graticule horizontally on the frame of an "artificial horizon" gyro and projecting its image into the field of view through a system of prisms and a semi-reflecting mirror.

Over the sea, tail drift sights are more useful than vertical sights because there is often no identifiable object beneath the aircraft, and when markers are dropped they trail outside the vertical field of view. Moreover, if the object observed is followed right back to the horizon, the tail sight is insensitive to roll. To offset this advantage, however, only objects over which the aircraft has directly passed must be observed ; this entails a special correction when using sea markers, since they fall dead astern of the aircraft and therefore not exactly on its track. Automatic linkages have been devised for mechanically correcting this "cross trail error" as it is called.

The Wind-Finding Attachment

Extremely accurate measurements of winds may be obtained by using a wind-finding attachment to the air position indicator. This attachment consists merely of an auxiliary set of dials which are driven from the mileage output shafts of the parent instrument but provide an enormously expanded scale, up to 10 miles N.-S. and E.-W., readable to 1/100 mile. In order to use it, the aircraft must be made to circle a selected point on the ground. The attachment is set in motion on first passing over this point and switched off on repassing it. If there were no wind the dials would register a zero change of air position. When there is a wind, the air position reached on completing the circuit is up-wind of the ground position by the distance through which the air mass has been blown during the orbit ; this can be read direct from the wind-finder counters.

The N.-S. and E.-W. components of wind velocity are therefore obtained by dividing the final readings of the wind-finder by the circuit time—generally three to six minutes.

The Radio-Altimeter

No up-to-date account of methods of wind-finding would be complete without a reference to the radio-altimeter. This instrument can measure the true height of the aircraft with great exactitude by timing the passage of a radar pulse from the plane to the ground and back again after reflection. One use of the instrument is in conjunction with the drift sight. It is possible to measure the angular rate of movement of a ground object by timing its passage across the field of view of a drift sight. Only if the height is accurately known, however, can this be converted into speed across the ground.

An even more recent use of the radio-altimeter is in the measurement of change in barometric pressure during flight, which provides, in particular, a means of "in flight" wind-forecasting. The height is held constant by the radio-altimeter and the absolute pressure is measured on a barometric altimeter—which is only a suitably calibrated and sensitive barometer. (It is generally easier to fly on the barometric instrument, reading the radio-altimeter.) Apart from the meteorological information gained, it can be shown that in high latitudes—with certain reservations—the aircraft is displaced sideways in flight by an amount directly and integrally proportional to the change of pressure during flight. The mathematics of this subject are rather beyond our present scope, but the principle is of interest since, although very approximate, a means of wind estimation is provided even when the ground is completely obscured by cloud.

As commercial flying develops, the importance of pre- and in-flight wind forecasting will no doubt be re-emphasized and the good aircraft captain will, like his windjamming ancestors of the sea, plan his track to catch all the following winds in order to make the quickest and most economical flights across the globe.

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CHAPTER IX

POSITION FIXING

All positions calculated by dead-reckoning processes, whether derived from a plot drawn by hand on a chart or from automatic instruments such as those described in the previous chapter, are liable to error, which is cumulative and proportional to the distance travelled ; the error arises mainly from faulty wind or current estimates, but also from the residual errors of the instruments used. To correct this "wander", absolute methods of checking the aircraft's (or ship's) position are necessary.

For simplicity these may be considered in three classes. First, there are the "bearing" instruments which measure the direction of the aircraft from a given ground station. Second, there are the "hyperbolic" systems in which the difference of the aircraft's distances from two ground stations is determined. Third, there is astronomical navigation in which position relative to the stars is observed.

There is a fourth class of "fixing" systems in which an aircraft is located by radar range measurements from ground stations, but these are omitted from consideration since they handle only one aircraft at a time and are therefore more useful as blind landing than general navigational aids.

Bearing Instruments

The principle of radio direction-finding is well known. A loop aerial is turned until its axis lies normal to the electric-magnetic wave front from a transmitting station, in which position the signal received is a minimum. Considerable advances have, however, been made from the simple manually rotated loop to the modern automatic radio-compass, which seeks and aligns itself automatically on the incoming signal, repeating the direction to a compass dial.

Loop

In one form the loop is carried on and rotated by the floating member of a differential gear, the driven members of which are rotated by two motors. In the absence of a signal the motors run at nearly equal speeds and the loop therefore drifts slowly round. Any signal received on the chosen frequency is applied to accelerate one motor and decelerate the other, and thus the loop is turned to the null position. A simple loop has two null positions 180° apart. The position "away" from the station is eliminated by adding (or

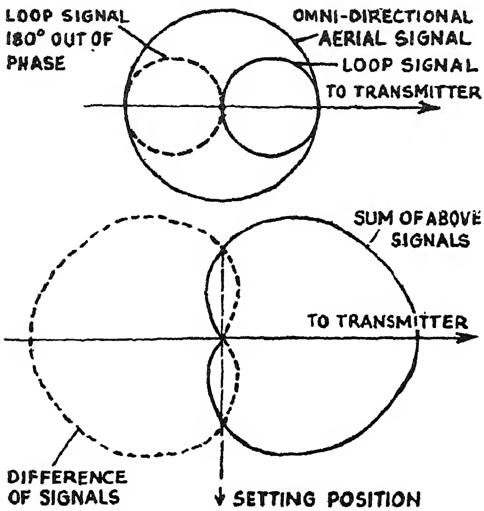

Fig. IX. 1. The radio-compass aerial system. Polar diagram showing signal strength received at different angles to the direction of the transmitter. (Strength is proportional to radius.)

subtracting) the signal from an omni-directional aerial to that of the loop signal. The two signals are in phase in one position of the loop and out of phase for the other; thus a cardiod-shaped directional response is obtained, Fig. IX. 1. A sharp null position is obtained by balancing the signals from the two cardiods, one obtained by adding and the other by subtracting the omni-directional and the loop aerial signals. The cardiods intersect in two equisignal points, but the phase of the unbalanced signal regulates the relative speeds of the loop motors so that the loop is always driven towards only one of the two setting positions, the other position being one of unstable equilibrium.

The direction of the incoming wave front is distorted by the metal of the airframe, producing the so-called quadrantal error. This and any instrumental error is corrected by inserting a differential gear between the scale from which the bearing is read and the loop. The floating portion of this gear is shifted by a lever bearing on a cam, thus introducing a small angular shift between the scale and the loop as the latter is rotated. The cam may be solid and specially cut for the particular type of aircraft, or alternatively in the form of a flexible annular strip of which the shape can be controlled by small adjusting screws. The setting of the loop scale is transmitted to a repeater dial, where it moves a pointer over a scale which is in turn oriented from the magnetic compass. The observer can, therefore, read the compass bearing of the station rather than its direction relative to the heading of the aircraft. The pointer is generally prolonged back across the dial so as to indicate also the reciprocal bearing or direction of the aeroplane from the station. It is the latter line which the navigator plots on his chart, two such bearings fixing his position.

The accuracy of radio bearings is not great, owing to the refraction of the electromagnetic wave front at coast-lines, reflections from mountains and atmospheric anomalies. They are used primarily

for homing and navigation in regions where suitable transmitting beacons are available not more than one or two hundred miles apart.

Beam

A reciprocal system to the radio-compass is the omni-directional beacon or "range". This is a transmitter beacon sending out a beam of radiation which rotates so that the amplitude of the signal received in an aircraft varies sinusoidally at about 50 c.p.s. The same beacon also sends out an omni-directional signal modulated at the same frequency as the rotating transmission. The phases of the two signals are adjusted so that along one direction they correspond exactly. On other bearings, however, there will be a phase difference between them proportional to the bearing of the aircraft from the transmitter. The receiving aircraft carries a phase meter graduated in degrees from which the bearing is read directly.

The omni-directional beacon has the advantage over the radio-compass that the aircraft need not carry a loop aerial. Its application is, however, more restricted since a special ground organisation is required.

In the U.S.A., beacons are extensively used for laying down narrow traffic lanes or beams known as radio ranges. Each beacon emits two sets of signals along directions at right angles, from aerials the polar diagram of whose emitted radiation is as in Fig. IX. 2.

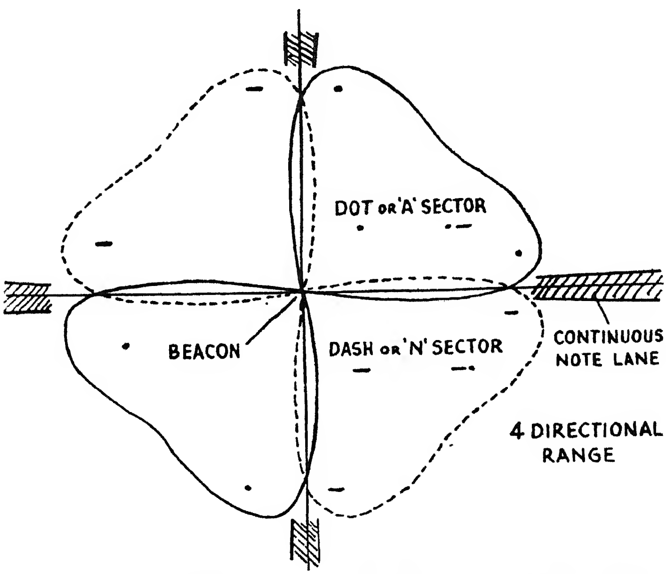

Fig. IX. 2. A Radio beam, showing the polar diagram of the radiation emitted.

One aerial sends out Morse dots and the other dashes. The lane is the narrow area common to the two signals where the rate at which signal strength falls off with angle is a maximum. An observer, listening on the transmitted frequency, hears dots on one side of the lane and dashes on the other. Signals received in the lane are of equal strength and, since the dots just fit the gaps in the dash signal, a continuous note is heard. The navigator or pilot thus has a continuous aural indication of his position relative to the lane, a continuous note if he is in it, dots if he is on one side and dashes if he is on the other. Interlocking A (dot-dash) and N (dash-dot) signals are often used instead of the simple dot-dash transmission because they are easier to interpret.

Radio ranges are suitable for large land areas such as the U.S.A., where there are prescribed traffic routes and the expense of maintaining closely spaced beacons is acceptable. Over extended sea passages and for long-range navigation, where the route is adjusted to take advantage of favourable wind and weather conditions, beam flying is impracticable and radio bearings are insufficiently accurate. For long-range direction finding over the Atlantic, therefore, the Germans developed the "Consol" beacon sometimes known as "Die Sonne".

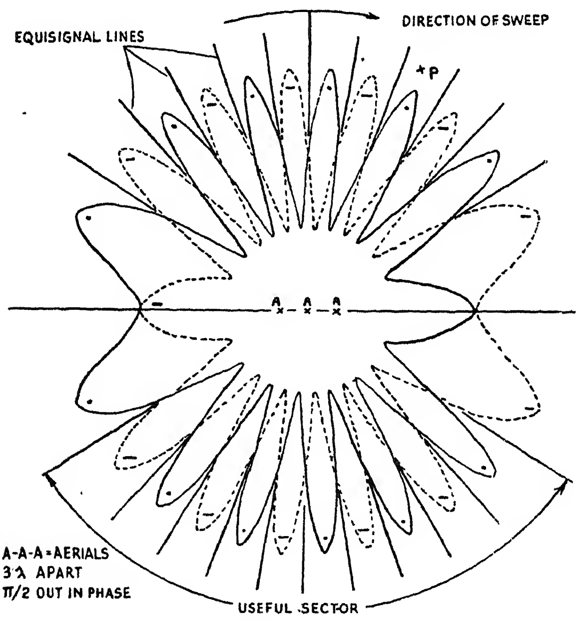

Fig. IX. 3. Consol radiation pattern, showing the lobes emitting dots and dashes. ('P' is the position of the aircraft.)

Consol or Die Sonne Beacons

This beacon consists of a transmitter sending out dots and dashes, as in the radio range. The aerial system is so arranged, however, that, instead of concentrating the radiation in two lobes, there are a number of closely spaced lobes intersecting in narrow equisignal "lanes" or bearing lines. (See Fig. IX. 3.) This radiation pattern is rotated (by phase adjustment, not mechanically) in accordance with a definite cycle, the transmission (dots and dashes) being started with the pattern centralised and stopped when each equisignal line has got to the position of its immediate neighbour. During this time 60 pulses, dots and dashes, are sent out. A navigator at the point P in Fig. IX. 3 will hear, say, 20 dots then a continuous note as the equisignal line passes across P and thereafter 39 dashes followed by a pause. The number of dots before the equisignal note, or dashes after, identifies his position in any given lobe of the radiation pattern in its centralised position. The particular lobe he is in can be identified by normal direction finding on a five second continuous transmission emitted after the dot-dash cycle. The width of the lobe is such that only about + or — 5° accuracy is required.

To facilitate plotting, the bearing lines corresponding to each dot-dash count are printed on a chart and position is fixed by the intersection of lines from two widely separated beacons.

The range of the system is about 1,000 miles and the accuracy of the bearing obtained is $\frac{1}{4}°$ to $\frac{1}{2}°$.

Hyperbolic Navigation Systems

The systems described in the previous section all use angular measurements to fix position somewhere along a radial line emanating from a single point, two such lines intersecting to define the position exactly. The hyperbolic systems are essentially range

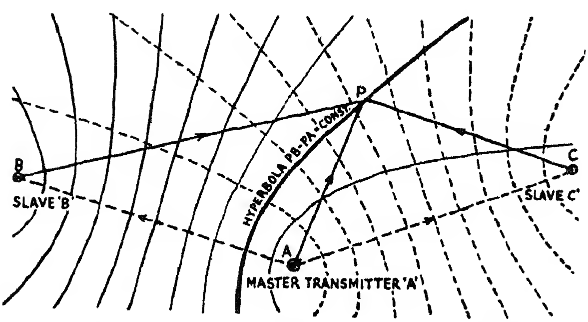

Fig. IX. 4. The principle of 'Hyperbolic' navigation instruments. A, B, and C are transmitters emitting the 'A', 'B' and 'C' pulses. 'P' is the position of the aircraft.

rather than angle measuring systems. Suppose signals are sent out simultaneously from two stations A and B (Fig. IX. 4); they will travel outwards with the speed of light and will therefore reach the aircraft at P with a small time interval between them equal to the path difference PA — PB divided by the speed of light. This time interval is the quantity measured. The locus of points whose path difference has any given value (PA — PB = Const.) is a hyperbola, hence the name. A whole family of these hyperbolas is printed on a special chart, each curve being marked with a number corresponding to the path difference in suitable units. Each time difference measurement fixes the position on one particular hyperbola, so that to locate the position exactly another pair of stations is introduced or a third station coupled to one of the first two. The time difference from this second pair of stations selects one of another family of hyperbolae printed on the same chart, generally in another colour, the intersection of the two loci giving the position. There are in general two such intersections but, except at points very close to the two stations, these are sufficiently far apart for the correct one to be identified from a dead-reckoning position. In some cases, however, a third locus can be obtained from a third pair of stations, thus removing any ambiguity.

Gee

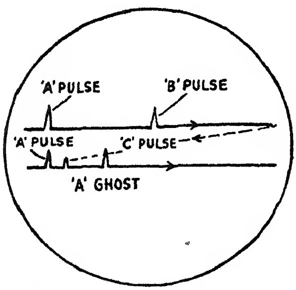

Fig. IX. 5. Signal trace on a 'Gee' indicator.

The methods of measuring the path difference vary from system to system. In the "Gee" system, a master transmitter "A" emits a short pulse which reaches the aircraft direct. On arrival, it forms a small vertical "blip" in a horizontal trace on a cathode ray tube which is made by a time-base synchronised with the rate at which "A" is emitting pulses. Each pulse also reaches a secondary or "slave" station "B" which it triggers, after a carefully regulated time delay, into sending out its own pulse. This "B" pulse appears as a second blip on the cathode ray tube trace, and the time representing the required path difference (plus the known delay time for the "A" signal to reach "B" and set it in motion) is the distance between the two blips on the trace. (In time units this is the ratio :

$$\left.\frac{\text{time difference}}{\text{pulse recurrence time of ``A''}}\right)$$

Instead of measuring the distance between the blips with a ruler, a second horizontal trace is introduced just below the first one on which are imposed regularly spaced signals like the marks on a ruler.

The distance between the blips can then be noted to the nearest whole mark, after which a small portion of both traces can be expanded enormously, thus forming a magnified image of the incoming blips and the relevant portion of the marker scale below them like a magnifying cursor on a slide rule. Great exactitude of measurement is obtained in this way.

The master transmitter "A" is normally arranged to trigger two slave stations "B" and "C" alternatively, i.e. ABAC, the particular "A" pulse preceding "C" being identified by a small "ghost" pulse ("a") coming just after the main "A" pulse. To get room for the whole presentation ABAaC across the cathode-ray tube, the trace is split into two and appears as shown in Fig. IX. 5.

The range of Gee is limited to about 200 miles, since the wavelength is very short and the propagation of the radiation therefore "optical" in character. The accuracy is high, varying from 1 to 2 miles at extreme ranges down to a fraction of a mile at points close to the stations and where the hyperbolae cut most nearly orthogonally.

Loran

The U.S.A. system "Loran" is similar to Gee but employs a longer wavelength. It has in consequence a greater range, being usable at 600 to 800 miles from the operating stations by direct transmission and up to 1,200 miles when the "sky wave" or radiation reflected from the upper atmosphere is used—the latter depends on favourable conditions, as short-wave wireless enthusiasts will know. The accuracy is not as good as that of Gee—5 to 10 miles at long range—but it was designed primarily for long-distance work where this is quite adequate.

Decca

The third system, "Decca," differs from the previous two in that the path difference from the two stations is measured, not by the position of blips on a cathode-ray tube trace, but by a comparison between the phases on arrival of radiation emitted continuously from the two transmitters. If the two signals are sent out in exact phase, their phase difference on arrival will be a measure of the path difference. The particular merit of the Decca system is that the phase differences are applied to phase meters so that a direct dial indication of position is given, thus eliminating the manipulation of the cathode-ray tube required in the other older systems. A disadvantage is that the system can give ambiguous answers. One revolution of the phase-meter dial, that is a 360° change of phase or one wavelength change of path difference, represents a relatively small change of position. The band between the two hyperbolae 360° in phase apart, or "lane" as it is called, is only a fraction of a mile in width. A second pointer geared to the main hand of the

phase meter is therefore provided to count the number of revolutions of the latter. If a short breakdown of the system should occur, however, and the craft should pass through a number of lanes without registering them on the dial, the position indicated on resumption of transmission would be erroneous. This can be guarded against to some extent by using a third hyperbola to check the position (if the three loci intersect in a triangle instead of a point, an error is indicated) and by keeping a continuous dead-reckoning plot. Nevertheless, since it has a very high accuracy and because there is less chance of missing a lane at the relatively slow speeds of marine craft, Decca seems in its present form to be more suited to sea than air navigation. Methods of lane identification are, however, being developed which may give it a more general application.

The range of Decca is 200 to 300 miles by night and somewhat greater by day.

In conclusion, it may be of interest to note that, if the two hyperbolic transmitting stations are placed close together the hyperbolae approximate closely to radial lines diverging from a point mid-way between them. The hyperbolic system then becomes an angular or bearing system.

The Post Office Position Indicator is a system of this kind. Two transmitters a few wavelengths apart are used and the phase difference of the radiations received from them is a measure of the bearing of the observer from the station.

Astronomical Position-finding

All the methods of position finding previously described are dependent on the co-operation of ground personnel and the maintenance of regularly spaced chains of transmitters. Astronomical methods avoid all such organisation and expense, rendering the navigator independent of contact with the ground. Unlike the radio methods, however, they are dependent on the attitude and movements of the aircraft and the accuracy, though independent of range from base, depends much more on the skill of both the navigator and his pilot. The reason for this is that astronomical navigation consists essentially of measurements of the position of the stars relative to a vertical datum line, which, except in the case of the natural sea horizon, is the direction of the earth's gravitational force as determined on board the craft. This direction is modified by accelerations which in the case of ships arise mainly from oscillations of the craft about its centre of gravity and in the case of aircraft from centrifugal forces due to the deviation of the aircraft from a straight path. Each minute of arc error in the direction of the vertical datum leads to one nautical mile error in the position determined.

The Gyro-Sextant

Theoretically, the ideal vertical datum would be a simple pendulum whose bob lay at the centre of the earth. Movement of the suspension point would not affect the bob and the direction of its string would thus provide a datum independent of accelerations. The period of a pendulum of this length is 84 minutes (under "g" at the surface of the earth) and it can be shown that any pendulum with the same period possesses a similar independence of acceleration. Unfortunately the production of a pendulum of such a long period is impossible in practice. The nearest to it is a gyro whose axis is precessed slowly towards the vertical by some gravity control—an artificial horizon in fact. Even the best artificial horizon has a period 50 to 100 times shorter than required, but fairly good results can be obtained provided the "period" of the gyro is long compared with that of the oscillations of the craft. The conventional type of gyro horizon, mounted in gimbals and precessed towards the vertical, has hitherto proved too erratic in performance for astro work. The spinning-top type of vertical has, however, been used successfully. Fig. IX. 6 is a photograph of a German bubble sextant to which has been added a gyro of this kind. The instrument has been taken down to show the gyro. This consists of a small rotor spinning like a top about a pivot which rests on a slightly concave surface. The top is accelerated by a jet of air directed on to small grooves machined into its edge, the air being fed from an outside source of pressure via the small entry tube. The air supply is disconnected and the gyro allowed to steady itself, before the observation is made, the shot being taken while the rotor is running down. On the rotor is mounted a lens with a graticule, representing the horizon, set in its focal plane. The axis of the lens lies diametrically across the rotor normal to its axis of spin, so that as the gyro rotates an image of the graticule, seen at infinity, is projected into the sextant in place of the natural horizon. The image appears continuous to an observer, although it is only presented once in each revolution—due, of course, to persistence of vision.

The Averaging Sextant

Another theoretical approach to the problem of providing an adequate sextant datum is to use a vertical datum, such as a bubble level, which follows the apparent vertical exactly and to measure the average position of this vertical relative to the stars. If the altitude of a star is measured relative to the apparent vertical in any craft, the error in the average value of the altitude over any period of time is proportional to the overall change in the component of the craft's speed measured in the direction of the star. If, therefore, the craft returns to its initial course and speed after a given time, the average altitude for this period will be the true one.

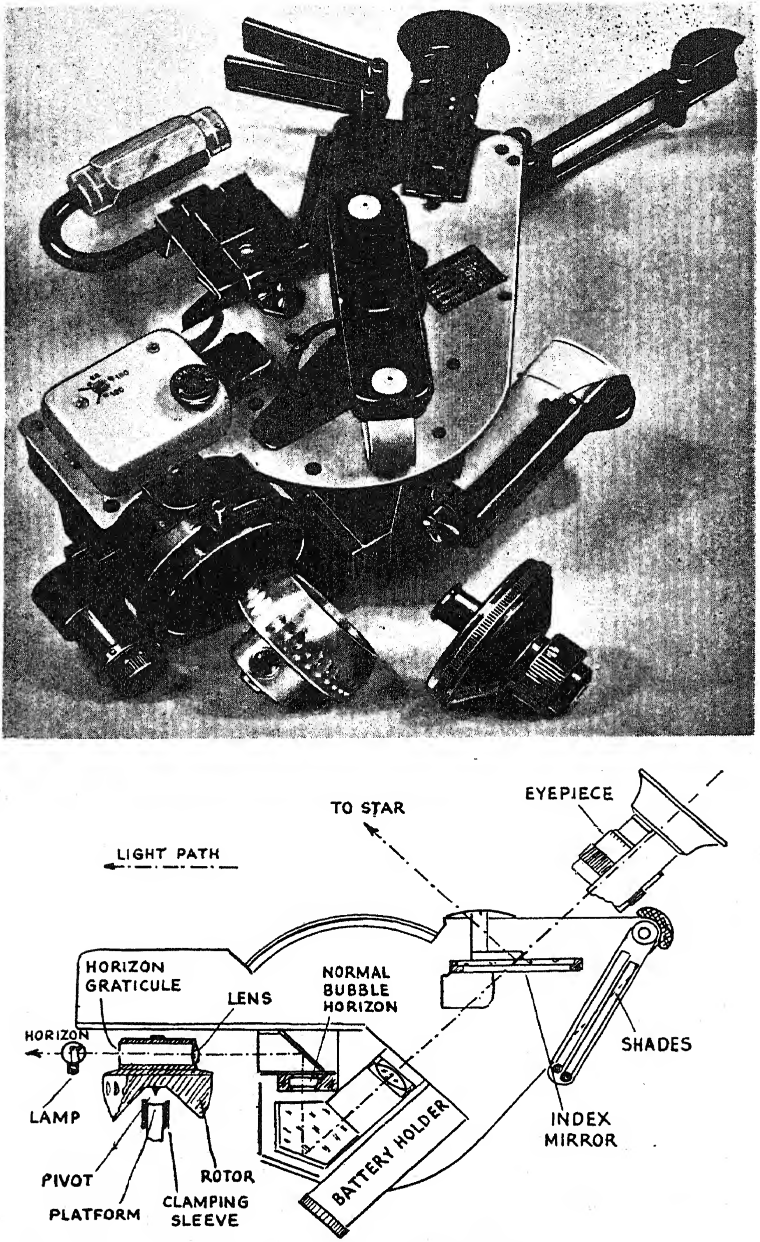

Fig. IX. 6. A German gyro-sextant (with explanatory diagram).

Fig. IX. 7 shows a British Mk. IXa sextant with averaging attachment. The observer sights the star in the normal way and then presses a small trigger which sets the clockwork averager in motion. He then keeps the star under observation, adjusting the altitude to the apparent value, for two minutes, at the end of which time the mechanism stops and the average altitude is shown in the small window.

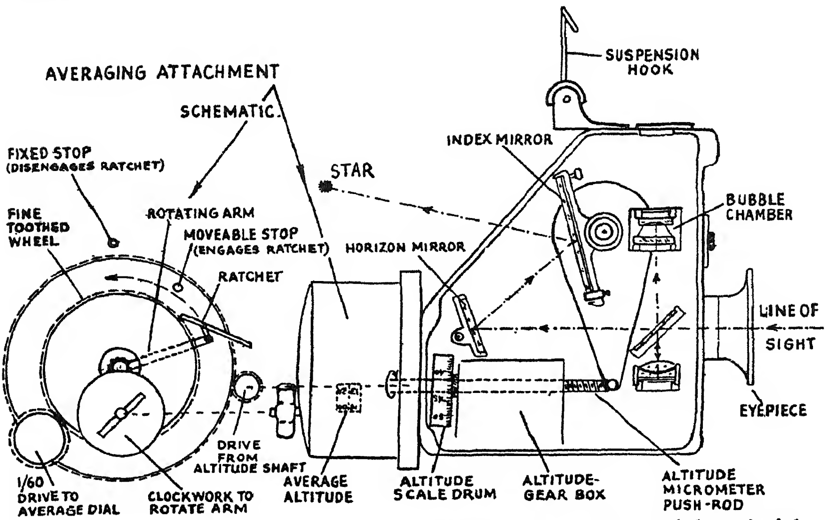

Fig. IX. 7. British Mk. IXa sextant, showing the optical system and the principle of the averaging attachment.

The principle of the averager is that a radial arm, carrying a small ratchet, is rotated continuously on a spindle by clockwork. Once every revolution a fixed stop forces the ratchet into engagement with a fine toothed wheel which is carried round with the arm until a second stop is reached which disengages the ratchet. This stop is mounted on a pinion connected to the altitude setting knob of the sextant, and is adjustable in position so that the fine toothed wheel makes a variable fraction of a revolution for every revolution of the ratchet arm according to the altitude setting. The fine toothed wheel drives the counter indicating the average altitude. The setting of the altitude stop is arranged so that each rotation of the arm adds 1/60 of the instantaneous altitude to the counter dials. The arm makes 60 revolutions (in two minutes), so that the final reading on the counter is $a_1/60 + a_2/60 \ldots\ldots + a_{60}/60$, i.e. the average altitude.

Several other types of averager have been tried successfully, some using friction gears, others are electrical. The chief requirements are compactness and a very light loading on the altitude knob of the sextant.

If we compare the merits of the gyro and the averaging device, the former is easier to use because the star is observed against a steady rather than a moving datum. However, a gyro must be much more fragile and expensive than an averager if it is to give comparable accuracy. If we wish to increase the accuracy of an averaged observation we have only to increase the averaging period—an easy change, within the limits of endurance of the observer. To increase the accuracy of a gyro entails a complete re-design and enormously increased fragility.

The two minute averaging period is chosen for aircraft because it corresponds roughly to the longest period of oscillation of a heavy aircraft in so-called straight flight.

Astronomical Calculations

At sea there is ample time to compute the locus of position from the observed altitude of a star, by conventional mathematical means. In the air, time is too short, and special tables or instruments are used. Tables are employed which give the altitude and azimuth of a selected number of the brighter stars at any time of the day at regular intervals of latitude and longitude. Even simpler is the Astrograph, an instrument the principle of which is illustrated in Fig. IX. 8. The quantity measured by a sextant (altitude or co-altitude of the star) is the range of the observer from a point on the ground where the star is immediately overhead—the zenith point. If the star stood still, relative to the earth, we could draw on the chart a series of range circles, just as we draw Gee hyperbolae, and identify our locus in this way. Owing to the rotation of the earth, however, the stars and their range circles move round the earth from east to west. To overcome this, the Astrograph projects the range circles on to the chart from a strip of film which can be unwound in an east-west direction on rollers. It is only necessary to adjust the rollers according to the time of observation for the position circles to be moved into the correct position.

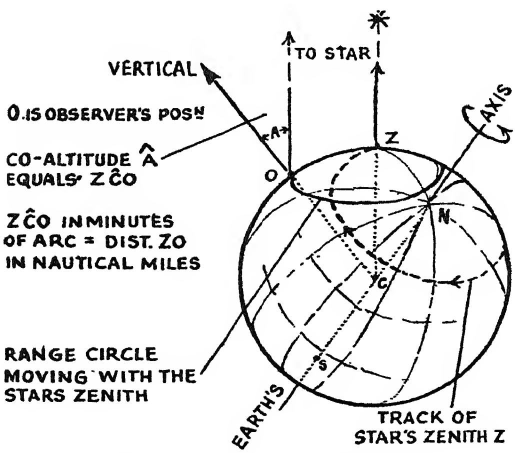

Fig. IX. 8. Principle of the Astrograph. A sextant observation locates the observer on an equi-range circle which moves round the earth from east to west.

The Astrograph is, of course, limited to selected stars whose position in the sky is fixed. When observing the moving bodies, such as the sun, moon and planets, tables must still be used, or, alternatively, one of the rather more complicated devices such as the Willis navigating machine, the German A.R.G. 1 Astronomical calculator or the Matthews computor. Space is too limited, however, to describe these in detail.

Two-Star Sextants

No account of astronomical position-finding instruments would be complete without mention of some of the "two-star" sextants which have been tried. From these instruments, position can be read off directly in latitude and longitude without calculation, but not less than two stars must be observed simultaneously.

The common principle of all these instruments is that the astronomer identifies every point in the heavens by two co-ordinates, a latitude—called declination—and a longitude (hour-angle). Declination and terrestrial latitude are the same; hour-angle and longitude differ only by a constant due to the rotation of the earth and depending only on the time. If, therefore, we can identify the celestial co-ordinates of a point in the sky immediately above us—the zenith point—our geographical co-ordinates can be found. The idea is best illustrated first by the theoretical instrument (Fig. IX. 9) which shows a transparent hemispherical globe, engraved with the stars in their correct positions in the sky, and filled with liquid, leaving a small bubble in the top. The eye is held at the centre of the globe, which is aligned so that the stars marked on it coincide with the actual stars in the sky. The bubble will then come to rest at the point on the globe representing the zenith of the observer's position. This point can be marked and its celestial co-ordinates measured on suitable scales. From these, the latitude and longitude can be found directly, if the time of observation is known.

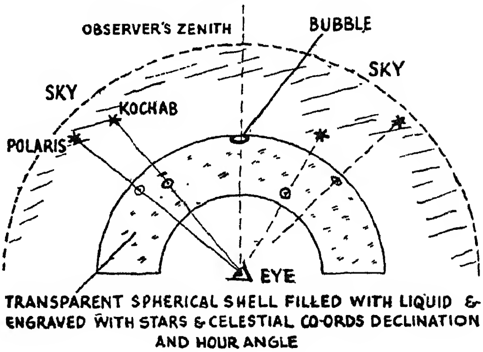

Fig. IX. 9. Principle of the 'Two-Star' sextant.

In practice only two stars are required to locate the hemisphere, so it can be replaced by optical systems pointed at two selected stars. A simple form of the instrument is the Hogg sextant illustrated in Fig. IX. 10. This consists of a telescope directed at the Pole star, with a subsidiary optical system for bringing the

nearby star Kochab into the same field of view. The telescope is held so that both stars lie in the centre of this field, and a circular spirit level, the image of which is also projected into the field of view, is adjusted until the bubble is centralised in its chamber. This is done by adjusting the bracket on which the level is carried, and which is carried on a sleeve surrounding the telescope to which it is pivoted about a diameter. Since the telescope is held parallel to the axis of rotation of the earth (at the Pole star), the angle between the bubble bracket and the optic axis of the telescope is the declination (latitude), and the angle of the sleeve, relative to the telescope, is a measure of the hour-angle (longitude plus time factor) of the observer's zenith. These quantities are read directly on the scales shown. (Fig. IX. 11.)

The drawback of two-star instruments is that they demand too much of the observer. He has to hold the instrument steady along two axes and to adjust the bubble in two directions all at the same

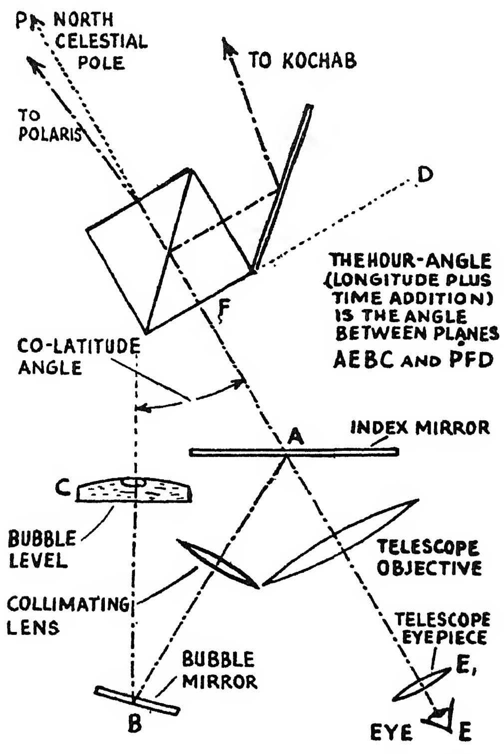

Fig. IX. 10. The optical system of the Hogg two-star sextant.

time. While this is feasible if the instrument is mounted on a tripod standing on the ground, it is well-nigh impossible in the air or at sea—at least with only one observer. It is possible, however, that gyro-stabilisation developments may bring these instruments into their own. Certainly the coming of stratosphere flying aircraft, moving above the clouds, is likely to increase the popularity of astronomical methods, and there is a wide field for developments in this sphere.

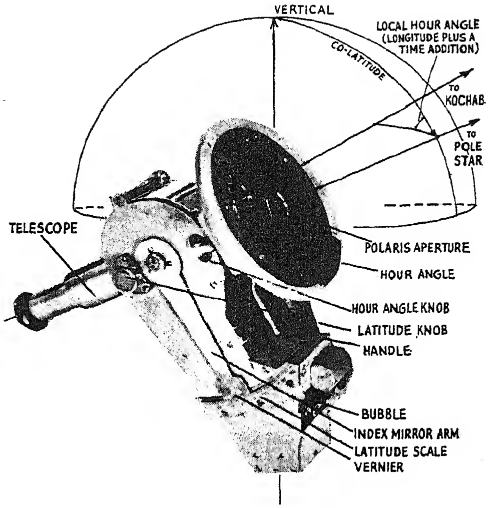

Fig. IX. 11. The Hogg two-star sextant.

The Astro-Compass

The use of the Pole star for determining the direction of the geographical north is common knowledge. If, however, the observer's position is known very approximately, north can be found by observing the direction of any other heavenly body. The Astro-Compass is used for this. It is employed in checking that the magnetic compass is functioning correctly; to detect changes in the magnetism of the hull or air-frame such as might be caused by the craft being struck by lightning or landed heavily; and as a primary direction indicator in polar regions where the earth's magnetic field is directed nearly vertically downward and a magnetic compass will not function satisfactorily.

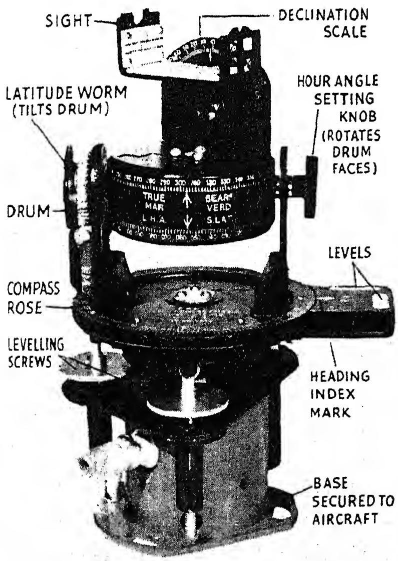

Fig. IX. 12. The astro-compass.

The principle of the Astro-Compass is illustrated in Fig. IX. 12 and 13. It consists of a rotatable bearing scale or compass rose which is adjusted by levels until

it is in a horizontal plane. Two brackets are secured to this rose; these carry a drum with rotatable flat faces, the drum being tiltable about the diametric axis through the brackets. The axis of tilt corresponds with the east-west direction on the rose. The tilt is adjusted by a worm gear until the angle of tilt equals the complement of the observer's latitude, so that, when the north point of the rose is directed along the meridian towards the north pole, the axis of the drum lies parallel to the axis of rotation of the earth. (Fig. IX. 13.)

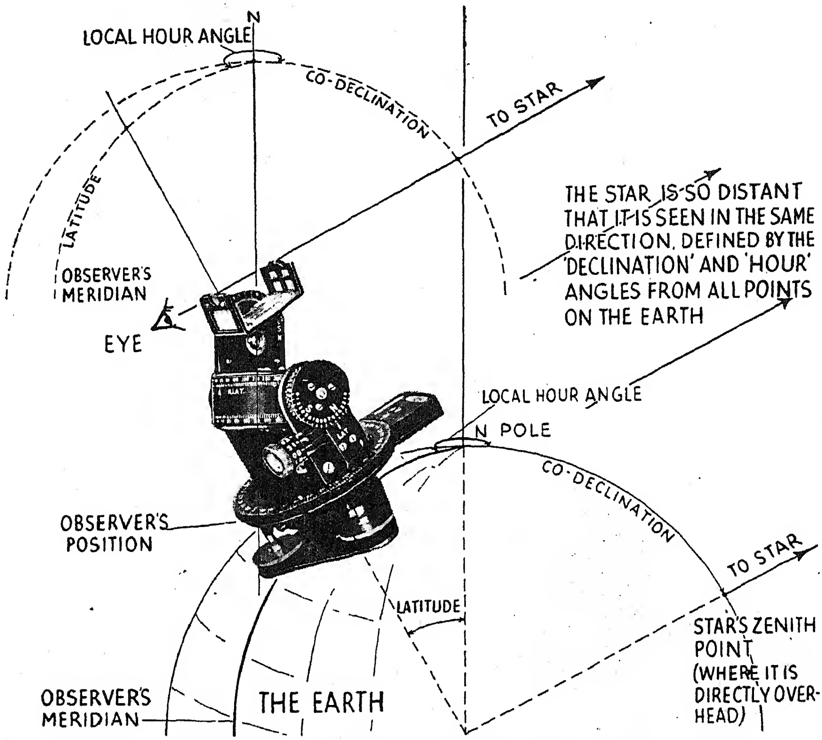

Fig. IX. 13. The principle of the astro-compass.

The drum carries a small optical sight on a bracket. This sight is rotatable in a plane parallel to the bracket through the axis of the drum. If the rose is correctly oriented, rotating the drum turns the sight about an axis parallel to that of the earth—equivalent to a longitude angle. Tilting the sight moves it in a direction corresponding to the latitude angle. The direction of any heavenly body is defined by two angular co-ordinates, declination—the analogue of latitude—and local hour angle—the analogue of longitude, quantities which can be obtained quite simply for any time of the day or night

and any observer's longitude with the help of the Air Almanac. The procedure, therefore, is : (a) to level the compass ; (b) tilt the drum for latitude ; (c) rotate it for local hour-angle ; (d) tilt the sight for declination. This sets up the instrument, so that all the observer has to do is to turn the rose until the sight is pointing directly at the star, when the compass course can be read off on the compass rose opposite an index mark on the base of the instrument.

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CHAPTER X

PRECISION TIME MEASUREMENT

Time is one of the fundamental units, and the accurate measurement of time therefore enters into many branches of scientific and technical work. In the majority of applications, it is only necessary to measure intervals of time, and no precise knowledge of absolute time is required. For the determination of velocities of projectiles or vehicles, speeds of rotation, or for timing many chemical or industrial processes, all that is required is a uniform time interval. For other purposes, such as surveying or navigation, absolute time is required, but in general the degree of accuracy of measurement necessary is lower than that demanded for the most precise measurements of time intervals.

The Fundamental Clock

The fundamental standard of time is dependent upon the period of the rotation of the earth on its axis ; so the determination of time is therefore an astronomical problem, and in each country the time system used is based on observations made at the national observatories. Unfortunately, the earth is not a perfect timekeeper ; its period of rotation is subject to small variations, the effects of which may not always be negligible. The astronomical equipment used has very few general applications, and for the present purpose it will be assumed that the practical standard is the time provided by an observatory, and made available to users by means of radio time signals.

Subsidiary Standards

Since time signals are not continuously available, a subsidiary time standard is necessary for interpolation between specific signals. Where moderate accuracy is sufficient, a watch or marine chronometer may be used. A high-class watch should maintain a uniform rate to within one second per day, and a marine chronometer to within half a second per day. With practice, watches and chronometers may be compared aurally with radio time signals to an accuracy of about a quarter of a second. Some chronometers are fitted with electrical contacts which close every second, and may thus be used to operate chronograph pens or a relay.

For higher accuracy, a pendulum clock may be employed. Even a comparatively simple weight-driven clock can be made to perform well if suitable precautions are taken, although a good regulator

with a seconds pendulum is naturally to be preferred. If practicable, the clock should be firmly fixed to a substantial wall as far away as possible from any machinery or other probable source of vibration. Some form of temperature control of the room in which the clock is mounted is most desirable. Under such conditions, a uniformity of rate of the order of one-tenth of a second per day may be expected, the residual variations being due partly to variations in the barometric pressure.

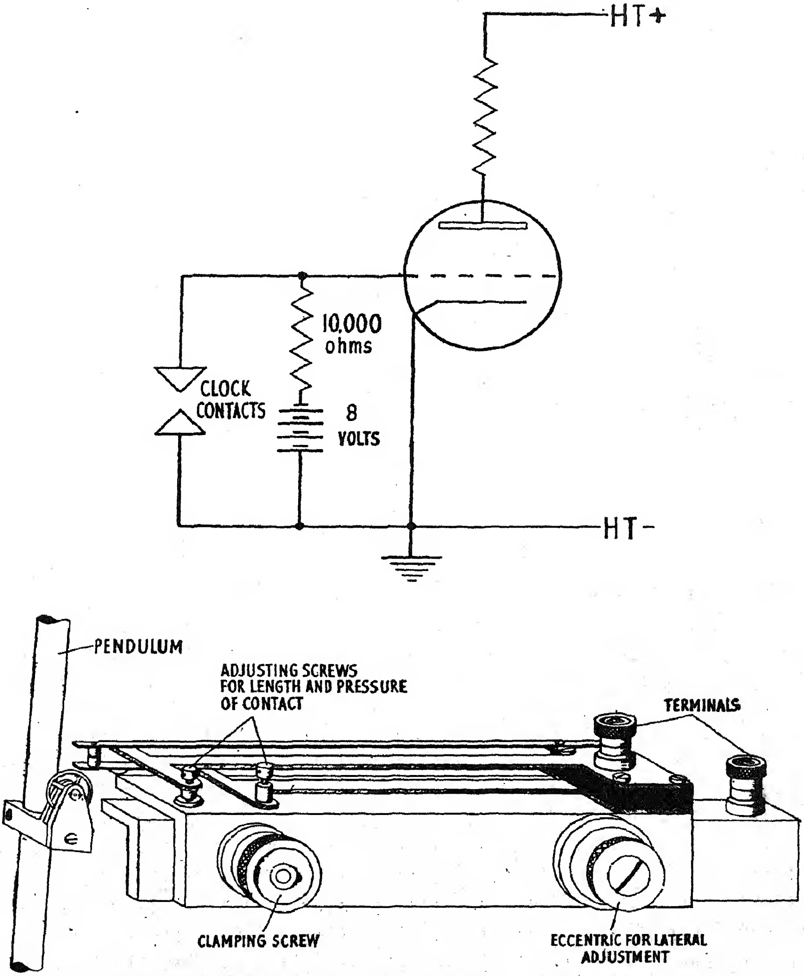

Fig. X. 1. (*Upper*) Electrical circuit as used for the control of the B.B.C. "six-dots" time signals and (*lower*) Seconds Contacts Assembly.

So that the time may be made available in the rooms or laboratories where it is required, the clock should be fitted with electrical contacts. Such contacts must be definite in action, but should be designed to impose the least possible load on the pendulum and movement. By using a valve relay it is possible to keep the current through the contacts to less than one milliampere. The risk of the contacts becoming dirty and uncertain in action is thus reduced. A typical mechanical design is shown in Fig. X. 1. A light well-balanced wheel, mounted in jewelled bearings, is attached to the pendulum. As the pendulum passes through the central position of each swing, the wheel rolls under a block on the lower contact-spring and presses it into contact with the upper spring. Each spring is provided with a vertical adjustment so that contact pressure and length can be varied. The whole contact assembly can be adjusted laterally to eliminate beat error.

Rate Adjustment

If a small tray is fitted to the pendulum, just below the movement, weights may be placed on the tray for the fine adjustment of rate. The addition of a weight raises the effective centre of gravity of the pendulum, thus making the clock run faster. The magnitude of the effect will depend on the height of the tray and the design of the pendulum, but in a typical case, the rate is altered by one second per day by the addition or removal of one gramme. With care, weights may be added or removed while the clock is going, and, each day after the clock has been checked by the time signal, a slight adjustment of the weights may be made to compensate for the effect of rate over the previous twenty-four hours.

There is a more convenient method of controlling the clock rate, which may also be used to adjust the clock error quickly. A permanent magnet is fixed to the pendulum and a fixed coil is mounted on a bracket on the case just below it. Arrangements are made by which the current through the coil can be adjusted or reversed. When the direction of the current is such as to cause an attraction between the coil and the magnet, the force is additional to the normal gravitational pull. Thus the clock behaves as if the gravitational force has increased, i.e., it goes faster. If the current is reversed, the electro-magnetic force is in the opposite direction to the gravitational pull, and the effect is as if the local force of gravity had been reduced, so that the clock goes slower. In a typical example, a current of 100 milliamperes alters the rate by approximately 15 seconds per day. Thus by leaving the magnetic-corrector on for one minute the clock may be advanced or retarded by one-hundredth of a second. This permits accurate adjustment, and the same coil may be used with a continuous current of a small fraction of a milliampere to compensate for the rate of the uncorrected clock.

Many forms of pendulum clock have been devised in which electro-magnets directly provide the maintaining power, or reset a gravity-operated impulsing lever. These have been fully described elsewhere, and will not therefore be considered in detail in this chapter. There are two types of particular interest, however—the Shortt-Synchronome "free pendulum", an account of which is contained in the previous volume, and which is probably the most accurate

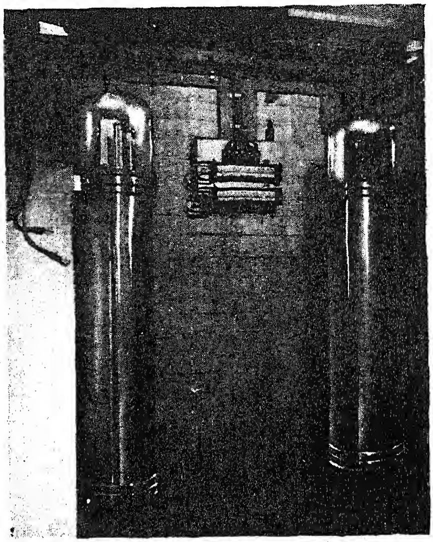

Fig. X. 2. The Shortt-Synchronome "free pendulum" in a temperature controlled room.

pendulum clock made, and the Hipp "Butterfly" escapement clock, which is simple, reliable, and still widely used. As will be seen from Fig. X. 3, a small freely-swinging lever hangs from the pendulum. As the pendulum swings, this lever trails backwards and forwards across a notched block on a contact-spring. As the arc of swing gradually falls, it reaches a certain critical value at which the trailing lever fails to clear the block. On the return swing, the end of the lever catches in the notch, forces the block down and closes a circuit. The current which is thus made to flow through the fixed coil below the pendulum, produces attraction of the soft iron block attached to the pendulum. The arc of swing is thus increased again. The process is then repeated. It will be noted that this device is independent of variations of the

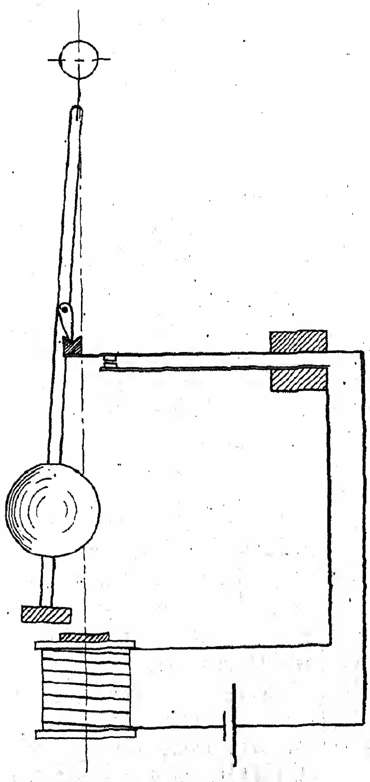

Fig. X. 3. Hipp clock.

battery voltage, since the pendulum is automatically impulsed as often as required. Such clocks have been reported as attaining a uniformity of rate of the order of three-hundredths of a second per day over periods of years and are very reliable in operation.

Quartz Clocks

Various forms of vibration clock have been developed in which the control is provided by a rapidly oscillating element instead of the slow swinging of a pendulum. For moderate accuracy a valve-maintained tuning-fork may be used, and a metal bar maintained in oscillation by magneto-striction has also been employed. Most attention has been paid, however, to the development of the quartz-controlled frequency standard as a clock. This has already proved its superiority over all other known clocks. The general principles of operation have been described in the previous volume, and descriptions of improved drive circuits and dividers may be studied in the references quoted at the end of this chapter.

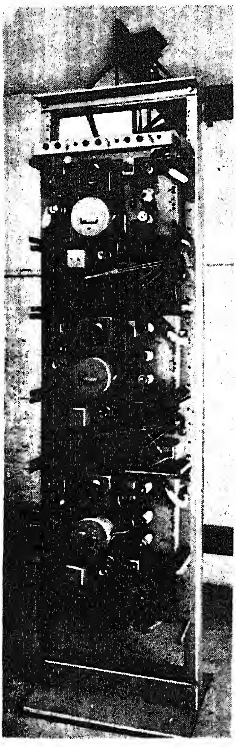

Fig. X. 4. Quartz clocks. Group of three of the primary standards at the Royal Observatory, Greenwich.

Considerable research has been devoted to the development of temperature-compensated quartz crystals. If the faces of the quartz plate are cut at certain definite angles to the axes of the natural crystal, it is possible to obtain a temperature/frequency relation which is comparatively constant over a short range of temperature. In the GT cut crystal, for example, the frequency of resonance varies only a few parts in 10^7 per degree centigrade change in temperature at the operating temperature. As the crystal is small, it may be conveniently mounted in a small thermostatically-controlled enclosure and temperature-controlled to within a few thousands of a degree. The effects of variations in the supply voltages, or in the values of the circuit elements and valve parameters, can also be reduced to almost negligible proportions, and a modern precision quartz clock should be capable of keeping within one or two parts in 10^8 of its predicted frequency. The corresponding stability of rate is of the order of one or two milliseconds per day. It may be noted that it is not usual to attempt to adjust the clock rate precisely, i.e., to adjust the frequency of the crystal to the exact

nominal value, which is usually 100 kilocycles per second. This would be very difficult, if not impossible, and even if it were feasible the rate would gradually change as the crystal aged. In general, the ageing of a crystal is approximately exponential, being rapid for the first few weeks and gradually settling down to a steady rate of frequency drift after some months. During the preliminary ageing period, while the rate of frequency drift is varying, the standard is of very little use as a clock, but when the drift has become comparatively uniform, the error E_t of the clock at any time t may be represented approximately by the formula :

$$E_t = a + bt + ct^2$$

where a, b and c are constants, a being the initial error and b the initial rate at time $t = o$, and $2c$ the rate of change of rate, or frequency drift.

The best quartz clocks are more accurate than pendulum clocks and have replaced them in many of the major observatories and for other purposes where the highest precision is required. They also possess various other useful features, one of the most important being the ease with which it is possible to compare the rates of two standards. The determination of relative rates is a straightforward measurement of frequency difference, which is usually carried out by combining the two nominal 100 kc/s outputs and measuring the beat frequency. If the frequency difference is small the beats can be counted by an electro-magnetic counter, and the change in the reading shown by the counter each day is a direct measure of the increasing time difference between the two clocks in units of one-hundred-thousandths of a second. The usual time comparisons may thus be supplemented by information concerning relative rates, and changes in rate may be more easily detected and measured.

It is advantageous to instal quartz clocks in groups of three. Intercomparison of rates by the beat counters will then indicate if one clock suffers any sudden change of

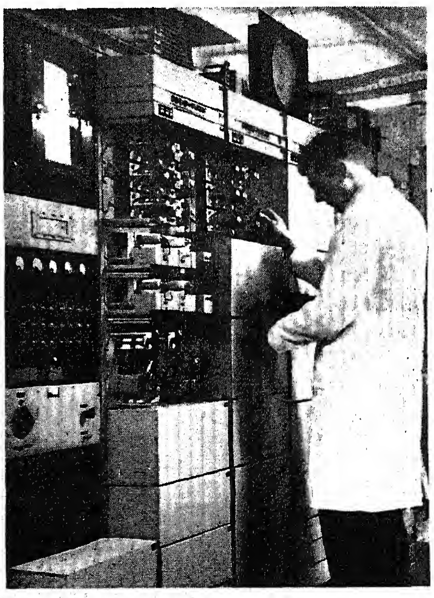

Fig. X. 5. Quartz clocks. Some of the dividers, beat counters and amplifiers at the Royal Observatory, Greenwich.

rate. The oscillators themselves should be in a temperature-controlled cellar, and the dividers, amplifiers and beat counters in a convenient and accessible position. It is usual to derive an output at 1,000 cycles per second, "locked" to the original 100 kilocycles per second of the quartz-controlled oscillator circuit. This low frequency supply is then amplified to drive a synchronous or "phonic" motor.

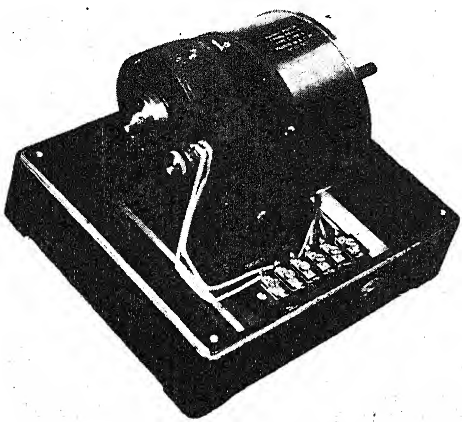

Fig. X. 6. Phonic motor fitted with contact drum for signals at one second intervals.

Contacts mounted on the motor shaft, or on shafts suitably geared to it, may be used to give electrical signals every second, every minute, or every hour. If desired, a dial and hands may also be fitted.

Since in general the quartz clock has a small gaining or losing rate, phonic motors are sometimes fitted with a phasing control to enable the contacts to be set to Mean Time. The motor shaft makes 10 revolutions per second, and drives a contact wheel at one revolution per second. The motor housing, or stator, is mounted in bearings and can be rotated by a hand control. One complete revolution of the motor casing thus changes the time of the contacts by one-tenth of a second, and adjustments of a fraction of a millisecond are easily obtained.

The 1,000 cycles per second output from the dividers can also be further divided electronically to 10 cycles per second and then converted into short sharp pulses which occur at intervals of one-tenth of a second. In this way the small errors due to hunting of the synchronous motor, or to variations in the mechanical contacts on the motor shaft, can be eliminated, and the electronically-derived pulses may thus be used as precise timing signals. If even higher precision is required, some of the original quartz-controlled 100 kilocycles per second sine wave may be converted into pulses. By electronic gating of these with pulses at the lower frequencies, single pulses at intervals of one-tenth of a second may be selected, and any errors due to phase-shift in the dividing circuit avoided.

Chronographs and Counters

For intercomparison of clocks, or for the comparison of clock signals with radio time signals or other timing pulses, there are four

main methods in which the following indicators are respectively used :

(a) chronograph (b) cathode ray tube
(c) null indicator (d) electronic counter chronometer.

The most widely used form of chronograph employs a narrow paper tape which is drawn at a uniform speed under two syphon pens which can be deflected independently by electro-magnets operated by the clock or timing signals. For field use, a spring motor with a governor and speed adjustment is used to draw the tape over the writing table, and syphon or bucket pens are fixed to armatures which are actuated by low resistance coils energized through relay contacts from a battery supply. For higher precision, a synchronous electric motor is preferred, and the gearing is designed to give a convenient time scale on the tape—say 5 cm. per second. Heaviness of pen-mechanism causes undesirable lag in operation, and in precision chronographs the pen-movements are light and very lightly damped.

One form of actuating movement is shown in the illustration (Fig. X. 7) of a chronograph by Muirhead & Co. Ltd., in which a torsion coil is used. Another useful form—slightly more robust—

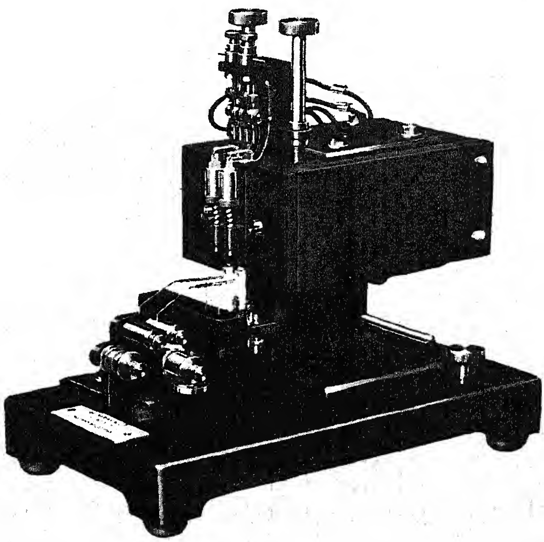

Fig. X. 7. Chronograph unit, employing torsion coil movements.

employs a moving-coil loud-speaker unit and a pivoted pen. The effect of lateral adjustment, or "parallax" between the two pens is eliminated if, after half the signals have been recorded, the connections to the two pen movements are interchanged by a reversal switch. This procedure also eliminates the so-called "electrical parallax" due to unequal response of the two movements to a signal of the same form and amplitude.

A trace, finer than is produced on paper by a pen, can be obtained on wax-coated paper by means of a steel stylus. The paper is coloured—usually red—and covered with a thin uniform wax coating. The steel stylus cuts through the wax and leaves a fine red trace. With careful handling, the records are quite durable and can be stored for future reference.

When it is desirable to have a long record convenient for examination, a drum chronograph with spiral trace is often more suitable. The drum may be covered with waxed paper or with slow photographic paper. If the drum is driven at one revolution per second by a phonic motor controlled by one standard, and the seconds contacts of another standard are connected to the pen movement, the relative rate can be measured conveniently by checking the inclination of the line drawn through the starting points of each signal. A Belin drum chronograph of this type, used at the Paris observatory, is illustrated (Fig. X. 8).

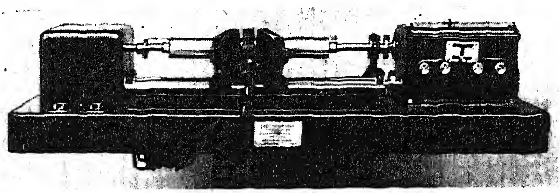

Fig. X. 8. Drum chronograph.

A high precision chronograph was developed at the National Physical Laboratory by Tomlinson & Sears. The signals operate two light steel markers. These make spiral traces on the smoked surface of a circular glass plate which is rotated at a uniform speed by a synchronous motor. Reading microscopes are fitted to the chronograph itself, and the plate is left in position for measurement. An accuracy of 0.1 millisecond can be obtained, but owing to the difficulties of exact re-centring of the plate the records cannot be checked to the same accuracy once the plate has been removed from the instrument.

To overcome the errors due to the lag of operation of a pen or stylus, Loomis used a spark registration method. A paper tape, 10 inches wide, was drawn forward in half second steps by the contacts

from one clock, between a metal block and a comb with one hundred insulated teeth. Each tooth was connected to a segment of a circular commutator. The commutator brush rotated ten times per second and the signals to be measured caused sparks to perforate the paper between the block and the comb tooth in circuit at that instant. 1/10th of an inch thus represented one thousandth of a second.

Cathode Ray Tube Methods

Lag due to mechanical inertia can be completely eliminated if a cathode ray tube is used as an indicator. The variety of measurements of this type is so wide that it is possible to mention only three diverse methods.

For the comparison of a radio time signal and a local standard the two signals may be fed to a double beam tube, or to a single beam tube adapted for dual traces by means of an electronic switch. The record is then obtained photographically on film or paper. One great advantage of the method is that an exact picture of the build-up of each signal is obtained, and this is of particular value when measuring radio time signals.

It is possible to obtain the same accuracy without the use of high film speeds if vertical movement of the film is combined with transverse movement of the spot by a linear time base. In the equipment used at the Observatory, the clock signal triggers the first scan of the time base, which is adjusted to sweep the full width of the film in about 4 milliseconds. At subsequent intervals of exactly 4 milliseconds the sweep is triggered by pulses derived from the clock. Vertical deflections are applied to mark the milliseconds, and, with smaller flicks, the tenths of milliseconds. The incoming radio time signal gives a large vertical deflection, and as soon as the build-up is complete, the beam is suppressed until the next clock signal is received. Thus the full build-up curve of the radio time signal is reproduced without any superposed horizontal traces.

For measurement of recurrent short intervals, such as the travel-time of a radar pulse, the whole measurement may be made from the visual indication on the cathode ray tube. Many radar and navigational indicators have been described in the technical press, and only one typical example, a navigational aid, will be referred to here. In the Loran system, the position of a ship is determined by measuring the time difference between the pulses radiated simultaneously from fixed shore transmitting stations. The function of the Loran indicator, therefore, is to measure the time difference between the two sets of pulses received at a repetition frequency of about 25 pulses per second, and an accuracy of 1 microsecond is necessary. The measurements are made in three stages, giving units and tens, hundreds and thousands of microseconds, a different frequency of the time-base-sweep being employed for each measure. The final

setting is obtained by applying adjustable time lags in the electrical circuits, and superposing the received radio pulses. Calibration markers are provided from a built in quartz-controlled oscillator. Instruments of this type can give very high accuracy and are convenient in operation, but are only suitable for measurement of pulses and short time intervals. The complete measurement can be made in less than one minute by a moderately well-trained operator, or in less than half a minute by an expert.

For intercomparison of clocks by means of the seconds impulses, or for the comparison of radio time-signals with clock-signals, Rohde and Schwarz use a null indicator with phasing control on the phonic motor of one standard. If the seconds pulses from clock A precede the pulses from clock B, a meter kicks to the left. The phasing control is adjusted until the signals from B just precede those from A, as shown by slight kicking of the meter to the right. The sensitivity of the meter is then gradually increased, but the accuracy obtainable by this method is limited by the scatter of the seconds pulses due to imperfections in the contact mechanism.

Counters and Chronoscopes

Electronic devices for measuring time differences are of two main types. Where moderate accuracy is sufficient, and robustness and reliability of the instrument is essential, it is usual to rely on the charge or discharge characteristics of a condenser which is charged by a constant voltage through a resistance. In an instrument of this type designed by Spilsbury & Felton, the range of measurement is from 2 to 1,000 milliseconds. The instrument is portable and self-contained, and the accuracy of measurement varies from 0.5 millisecond on short intervals to 0.5% for long intervals. The principle of operation is shown in Fig. X. 9.

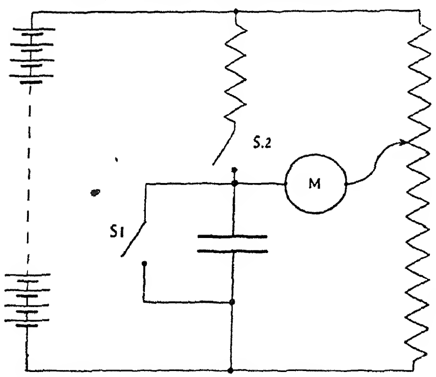

Fig. X. 9. Basic circuit of chronoscope.

Switches S1 and S2 are closed. The first impulse opens S1 and the condenser voltage rises exponentially until the second impulse opens S2. The setting of the potentiometer slider is then adjusted to give a null indication on the valve voltmeter M. In practice, decade dials are used, and the final reading is converted into milliseconds by reference to specially prepared tables.

For higher precision, counter chronometers are employed. A typical instrument of this type was developed by Cinema Television

Limited in collaboration with the Ministry of Supply for the determination of projectile velocities. Such instruments are now very widely used for accurate measurement of time intervals, but they are comparatively complex and expensive, and they require skilled maintenance. The standard unit provides for three operating frequencies, 100 kc/s from a quartz oscillator, 1 kc/s from a fork, and 100 c.p.s. derived from the mains supply. Alternatively, an external precision standard may be used to supply 100 kc/s, 10kc/s, 1 kc/s and 100 c.p.s. The electrical impulses between which it is desired to measure the time interval are sharpened and applied to "start" and "stop" trigger circuits. From the operation of the start impulse until the triggering of the stop circuit the constant frequency supply is fed to a counting unit, which will, in the case of 100 kc/s per second supply, count the number of complete cycles (i.e., one-hundred-thousandths of a second). When less accuracy will suffice, a lower operating frequency can be employed, and the 1 kc/s supply, for example, will permit counting in units of thousandths of a second. The circuit employed is a modification of the well-known "scale-of-two" counters, first developed in connection with geiger counters, and using hard valves in units comprising a scale of two and a scale of five in cascade, giving a scale often divisions per unit. Five decade dials indicate the state of each unit at the end of a count, and may be read off directly in decimals of a second. A printer unit has been designed as an accessory and will provide a printed record of the measures made.

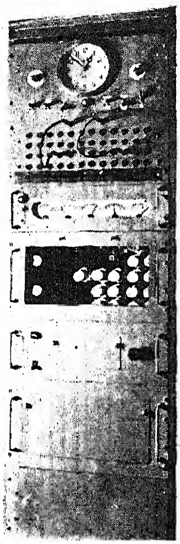

Fig. X. 10.
Decimal counter chronometer.

If the intervals to be measured are nominally equal, but subject to erratics, ten successive counts may be made without re-setting the meters, and the mean of ten readings is thus indicated directly. At the Observatory, for example, the start circuit is operated from a standard clock and the stop circuit by received radio time signals. After ten counts the readings of the meters give, to five figure accuracy, the mean of ten measures of the amount by which the signal is slow on the clock. In an interesting variant of the decimal counter chronometer, the meters are replaced by ten-way switches. A required time interval may be set up on the switches, and at that interval after receipt of a start signal, the instrument emits a pulse.

Watch Rate Recorders

A specialised form of chronograph has been developed for the rapid determination of watch rates. Such recorders have only

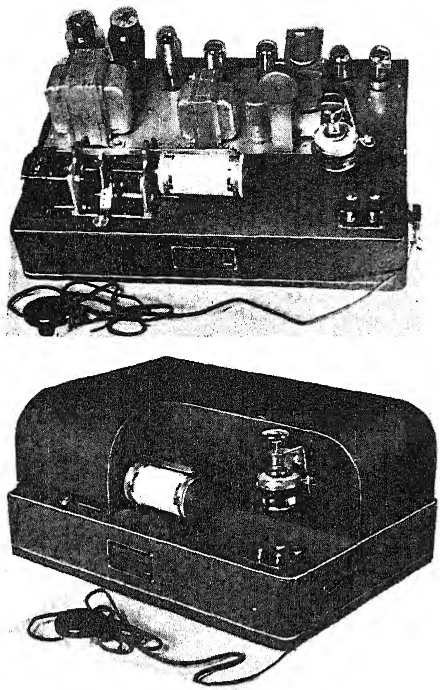

Fig. X. 11. Watch rate recorder.

limited applications as they can be used only to determine the rate of the watch over a short period, and it is 24-hour rates that are of more interest. They may be used, however, for routine inspection of medium grade watches, or for determination of positional errors of precision watches. In general, the time standard is provided by a built-in quartz crystal or fork controlled oscillator, and a sub-multiple frequency drives a motor which moves the tape or recording drum at a constant speed. The watch ticks are picked up by a microphone and amplified to operate a pen or stylus which marks the drum or tape record. A linear series of dots on the paper indicates, by its inclination, the rate error of the watch. Irregularities in the record are usually present owing to eccentricity or want of adjustment in the watch movement, and to an experienced operator far more information than the mere rate can be deduced.

Radio Time Signals

As mentioned earlier, for most practical purposes it is necessary to accept as the standard for time measurement the radio time signals controlled from the major national observatories. The Royal Observatory, Greenwich, is responsible, in Great Britain, for the maintenance of the national time service, and, by international agreement, the standard times in nearly all other countries are directly related to Greenwich Mean Time. A service of time signals, adequate for normal domestic needs, and for many scientific and navigational purposes, is controlled from the observatory and radiated by the B.B.C. These signals—"the six pips"—at intervals of one second, the last of which denotes the exact quarter hour, are normally maintained within one-twentieth of a second of Greenwich Mean Time.

Where higher precision is required, however, use should be made of the rhythmic series of time signals radiated twice daily by the Post Office Rugby Radio Station, GBR, on a frequency of 16 kc/s, and on associated short wave transmitters.

The signal is preceded by the morse announcement GBR, GBR, TIME, and a tuning dash. The time signal consists of a dash starting at each minute from 0955 to 0959 followed by 60 dots, and terminating with a dash which starts at 1000. A similar signal is radiated in the evening from 1755 to 1800. As these signals are widely used for checking frequency standards, special attention is given to ensuring the highest possible uniformity of rate, and the twenty-four hour interval defined by the 1000 signals on successive days is normally accurate to within about two-thousandths of a second.

These signals provide a world-wide service, and as the wave-length is very long, the travel time of the radio signals to a distant reception site may be fairly accurately estimated and allowed for. There is, however, the disadvantage that as the transmitted frequency is so low, the build-up of the signal pips is slow, and accurate measurement of the time of commencement of the signals correspondingly difficult. A specially designed receiver is essential and some means should be provided for measuring the lag and daily variations in lag of the radio receiver.

In America, the National Bureau of Standards at Washington maintains a continuous service of time signals which are superposed on the WWV standard frequency transmissions on 2.5, 5, 10, 15, 20, 25 and 30 Mc/s. Plans are under consideration for the establishment of similar services providing a constant emission of time signals and standard frequencies from four or five different stations which would ensure continuous world-wide coverage. Such a scheme would not only entail full technical co-operation between the participating countries, but would necessitate a higher standard of agreement between widely separated observatories than has been attained in the past. It would, however, be of inestimable value to navigation, surveying and many branches of scientific work, and the problems involved are receiving careful attention by the appropriate authorities in Great Britain, and it is hoped to arrange test transmissions on a limited scale in the fairly near future.

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SECTION 3

ELECTRICAL INSTRUMENTS

CHAPTER XI

ELECTRICAL MEASURING

Most of the commonly used electrical instruments have been described in Chapter XII of *Scientific Instruments*; this chapter describes a number of the more important instruments for more specialised use.

Voltage Measurements

Most voltage measurements are direct or indirect comparisons with the voltage produced by a standard cell. Standard cells are made of chemically pure materials and are characterised by a very constant electro-motive force (e.m.f.). When a cell supplies current, however, the potential difference (p.d.) developed between its terminals is lower than its e.m.f. because of the voltage drop in its internal resistance. For this reason and because a standard cell will be damaged if made to supply an appreciable current, measuring apparatus must draw little or no current from the standard cell.

The Potentiometer

The Weston standard cell has an e.m.f. of just over 1 volt, and this e.m.f. may be compared with greater or small voltages by means of a potentiometer. This, in its simplest form, consists of a long uniform wire stretched along a graduated scale. A steady current is passed through the wire so that a p.d. is set up between any two points on it. A standard cell is connected to one point (P) on the wire and through a sensitive galvanometer to another point (Q), the connections being made so that the e.m.f. of the cell and the p.d. across PQ of the wire act in opposite directions in the galvanometer circuit. The separation PQ is then varied until a point is found such that the galvanometer shows that no current is flowing through it. The p.d. across the length PQ is then equal to the e.m.f. (E) of the standard; if the wire is perfectly uniform, the p.d. across any other length AB is equal to $\frac{AB}{PQ}$ E. volts. Any other p.d. may now be measured by balancing it similarly against the p.d. across a length of the potentiometer wire.

In a more accurate form the slide wire is connected in series with ten (or more) coils of wire each having a resistance equal to that of the slide wire. The effect is as if the slide wire were eleven times as long; coarse adjustment is made by connecting to the junctions of the resistances, fine adjustment by a motion of a slider along the

wire. For measurement of voltages much in excess of 1 volt a "volt box" is used; this is a resistance tapped at known fractions of its total value. To measure a p.d. of about 600 volts the resistance would be tapped at 1/600 of its total value, and the p.d. across the small portion measured on the potentiometer.

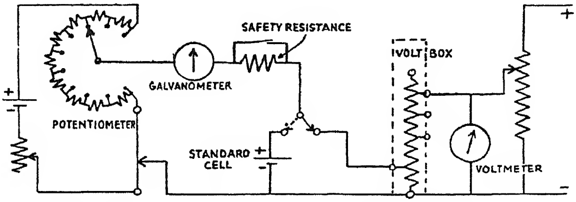


Fig. XI. 1. Circuit for voltmeter calibration by potentiometer.

Fig. XI. 1 shows the calibration of a 0—250 voltmeter, the potential divider being set to make the voltmeter give a convenient reading; the actual p.d. across the voltmeter is then found from the potentiometer reading and the volt box ratio.

Valve Voltmeters

These incorporate a vacuum diode or triode and are used to measure alternating voltage where the current taken by an ordinary voltmeter would be excessive, or where the frequency of the voltage to be measured exceeds a few thousand c.p.s. A well-designed valve voltmeter has a calibration which is independent of frequency up to several megacycles per second. For convenience the calibration is usually made in R.M.S. voltage. In many cases the deflection of the instrument is proportional to some quality of the voltage (e.g. the peak value) other than the root-mean-square; in such cases the instrument only reads correctly if the waveform of the voltage is sinusoidal.

Peak Voltmeters

A simple but accurate circuit for measuring peak values is connected as shown in Fig. XI. 2. In the absence of the input voltage, the direct voltage is adjusted to such a value that the anode current

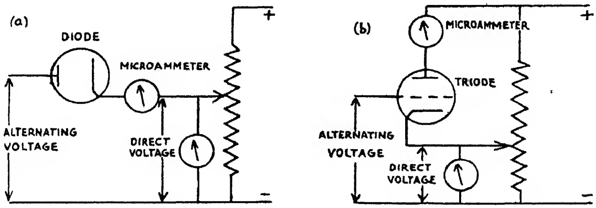


Fig. XI. 2. Peak reading valve-voltmeters. (a) Diode voltmeter. (b) Triode voltmeter.

of the valve just ceases. When an input voltage is applied the galvanometer registers a current and the direct voltage is again adjusted until the current just ceases. The difference between the two direct voltage readings is then equal to the peak value of the input voltage.

Another peak voltmeter is shown in Fig. XI. 3. The application of an input signal causes the diode to conduct when its anode is positive to cathode. The condenser charges up until the p.d. across it is equal to the peak value of the input voltage when the diode no longer conducts, and the p.d. across the condenser remains constant and is recorded by the electrostatic voltmeter. A condenser with negligible leakage is used so that the condenser can discharge only very slowly. This makes it possible for the circuit to record the peak value of a surge; for after a surge the input voltage falls, the diode anode becomes negative to cathode and the condenser cannot discharge.

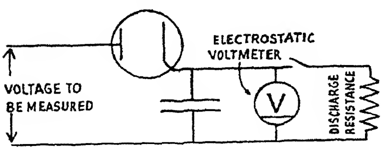


Fig. XI. 3. Circuit of valve-voltmeter to measure surge voltage.

Diode Rectifier Voltmeters

This circuit uses the diode as a rectifier. A load resistance, large compared with the anode-cathode resistance of the diode, is used, and a moving-coil microammeter records the mean value of the rectified current.

In a modification of this circuit the rectified voltage developed across the load resistance is used to change the grid voltage of a triode, and the resulting change of anode current is recorded by a moving-coil meter. This allows the use of a high diode load resistance (about 2 megohms) and consequent small input power without the necessity for a very sensitive microammeter.

Such circuits may be used to measure voltage at any frequency between about 15 c.p.s. and 300 megacycles/sec., if care is taken to keep stray capacitance very small. Waveform errors result if the input voltage is non-sinusoidal.

Triode Voltmeters

The most usual form of these uses a valve with a steady negative grid bias such that the operating point is in a region of high characteristic curvature (Fig. XI. 4). The superposition of an alternating voltage on the steady bias causes the anode current to rise more during positive half cycles than it falls during negative half cycles, so that the mean anode current rises. The change of anode current is registered by a moving-coil meter and may be calibrated in terms of the input voltage. In general, no simple law relates the change of

anode current with input voltage ; usually the rise of anode current is small for low voltages and disproportionally greater for larger voltages.

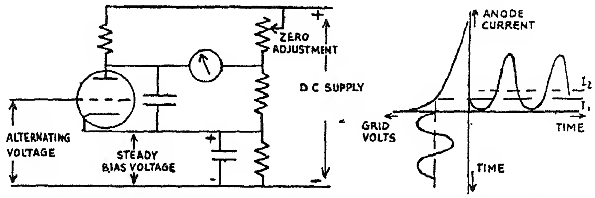


Fig. XI. 4. Triode valve-voltmeter. The applied signal raises the mean anode current from 1_1 to 1_2.

Some versions of this valve voltmeter include a resistance, by-passed by a condenser, in the cathode circuit. The rise of anode current increases the potential drop across the cathode resistance and increases the negative grid bias, so that greater input voltages are required for the same change of anode current.

Most triode voltmeters show waveform errors when the input signal is non-sinusoidal. It is, however, possible to choose an operating point such that, with restricted input signals, the change of anode current is proportional to the square of the applied alternating voltage ; in this case the meter can indicate true R.M.S. values whatever the waveform of the voltage.

The great merit of the triode voltmeter is that it absorbs no power. This condition is vitiated if the input signal is too large, or if feed-back can occur in the circuit. The former trouble can easily be avoided ; the latter is obviated by connecting the anode of the valve to its cathode through a condenser of such a capacitance as to prevent the valve from amplifying.

Rectifier Voltmeters

These are widely used for measuring alternating voltages with frequencies between ·15 c.p.s. and 50,000 c.p.s. The rectifier is usually a copper plate coated with copper oxide ; the contact conducts quite well in one direction and offers a very high resistance to a flow of current in the reverse direction. Four rectifiers are usually connected in a bridge circuit (Fig. XI. 5), so that no matter which way the applied voltage acts the current through the moving-coil meter is always in the same

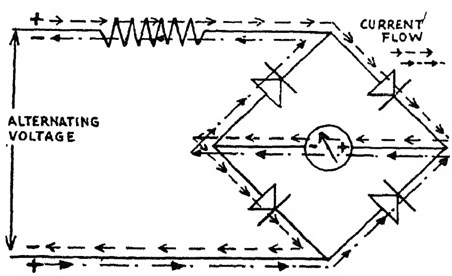


Fig. XI. 5. Bridge connected rectifiers. Dotted arrows show the current flow in alternate half cycles.

direction. The resistance offered by the bridge decreases as the current through it increases, so that in a low range voltmeter the scale is cramped at the lower end. The effect is unnoticeable in ranges for more than 20 volts full scale because the series resistance is much greater than the bridge circuit resistance.

High Voltage Measuring Instruments

A sphere spark-gap is used for the accurate measurement of voltages greater than 10,000. The p.d. to be measured is applied between two accurately machined brass spheres and the spacing between them adjusted until the intervening air breaks down to give a spark. Tables have been prepared showing the breakdown voltage for various diameter spheres under specified conditions of atmospheric pressure and humidity.

A form of voltmeter often used utilises the force between two plates between which a p.d. exists. One plate is fixed to the case of the instrument and the other geared to the pointer. The force between the plates is inversely proportional to the square of the spacing between them and in some instruments this spacing can be adjusted to alter the range of the meter. Some instruments of this type have air as the medium between the plates; in others the electrodes are immersed in oil which reduces the liability to spark over, and allows smaller spacings and greater forces to be employed. Voltmeters of this type have been made for full scale readings of up to 200 kilovolt.

In the "ionic wind" voltmeter a motion of air, caused by repulsion of charged ions from the neighbourhood of a point, cools a heated wire. The change of temperature of the wire changes its resistance and so causes the deflection of a moving-coil meter. A Wheatstone bridge circuit is usually used with the wire as one arm of the bridge. The indications of this voltmeter are affected by various factors, such as the state of the gas in which the ionic wind is set up, and they are also subject to waveform errors.

The range of an ordinary electrostatic voltmeter may be extended by a potential divider consisting either of two resistances or of two capacitances connected in series across the voltage to be measured, with the voltmeter connected across one of them. In either case the voltmeter measures only a fraction of the total p.d.; with resistances a fraction $\dfrac{R_2}{R_1 + R_2}$, or with condensers a fraction $\dfrac{C_1}{C_1 + C_2}$ where R_2 or C_2 is the component across which the voltmeter is connected. If condensers are used these should be good quality air condensers, or leakage across them and conduction through them will affect the readings.

In the neon crest voltmeter a neon lamp is connected across a variable capacitance C_2 in series with a small fixed capacitance C_1. The neon conducts and glows when the p.d. across it exceeds a certain critical value which may be accurately determined. The p.d. to be measured is applied across C_1 and C_2 in series and C_2 then adjusted until the neon just strikes ; the applied voltage is then given by $\left(\frac{C_1 + C_2}{C_1}\right). V$ where V is the striking voltage of the neon. The neon lamp must be protected from stray electric fields and from strong lights, since these affect the striking voltage. This instrument measures the peak value of the applied voltage.

Current Measurements and Detection

A current balance is used as a secondary standard for the measurement of current. A beam is suspended freely at its centre by flexible ribbons of very fine copper wire carrying identical coils at either end. Above and below each of these coils are other coils which are fixed in position. The coils are connected in series and the current to be measured passed through them, so that the reaction between the magnetic fields of the fixed and movable coils causes a force to act between them. The connections are so arranged that if the force on one end of the beam is down, that at the other is up, and a turning moment acts on the beam. The turning moment is proportional to the square of the current and is balanced by moving a slider along a graduated scale ; the current may then be determined from the position of the slider. This balance may be used to measure either alternating or direct currents.

An ammeter seldom described is illustrated in Fig. XI. 6. It is a moving iron instrument in which the armature lies in a gap in an iron ring. The current to be measured is passed through a coil wound on the ring and causes a magnetic field to be set up in the air gap. The magnetic field turns the armature against a spiral spring and moves the pointer over the scale. The ring is made to project beyond the instrument casing so that any required number of turns may be wound on it. The scale of the instrument is therefore adjustable—the greater the number of turns, the smaller the current needed for full scale reading. Usually the ring is split and hinged, thus enabling it to be closed around a cable carrying current ; this

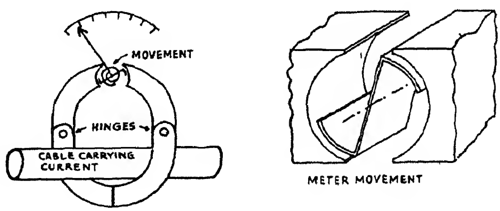
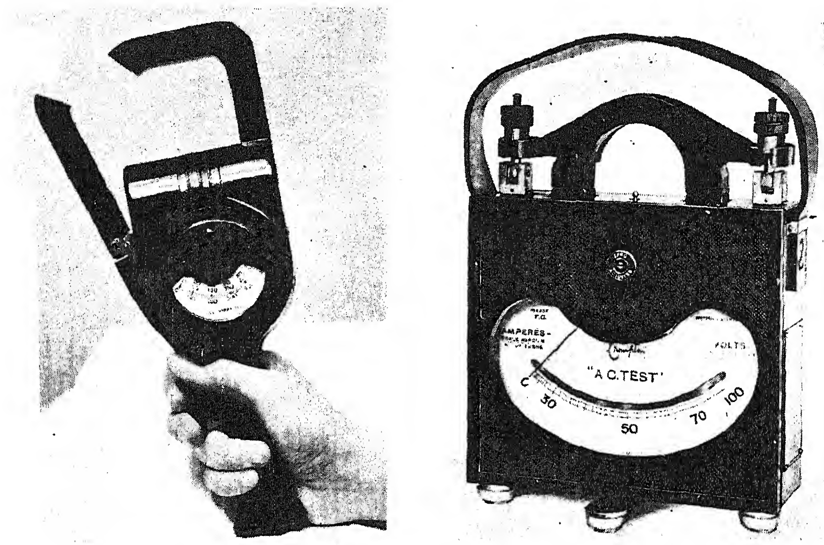


Fig. XI. 6. Illustrating the construction of adjustable range moving iron ammeter.

provides a one-turn coil on the core and the meter may thus be used to measure heavy currents without interrupting the circuit. This meter may be used for direct or alternating current and indicates R.M.S. values.



(a) (b)

Fig. XI. 7. Commercial forms of adjustable range moving iron ammeter.

For the detection of smaller direct currents, very sensitive moving coil or moving magnet instruments are used ; the moving element carries a mirror which reflects a spot of light on to a scale usually about one metre away. The D'Arsonval galvanometer is one of the most widely used types. In construction it is similar to a permanent magnet moving coil ammeter, but the coil carries many turns of fine wire and is suspended by a fine strip of phosphor bronze. The controlling torque is produced by the twisting of the suspension and may be extremely small for a given angle of twist. Such instruments can detect currents of less than 10^{-10} ampere.

The Vibration galvanometer is used for the detection of low frequency alternating currents of the order of 10^{-7} ampere. This instrument is similar to the D'Arsonval galvanometer, but the length and tension of the suspension are adjustable and a very light coil and mirror are used. In use, the operator adjusts the length and/or tension of the suspension until the natural resonance frequency of torsional vibrations of the system is the same as the frequency of the alternating current. The mirror then swings from side to side and reflects a band of light on to the screen. The instrument is sharply

selective, responding readily to currents at its resonance frequency but hardly at all at frequencies a few cycles removed.

Magnetic Measurement

Many methods have been devised for measuring magnetic field strength, but few are suitable for general use. One instrument which can be used for this purpose is the moving iron ammeter (Fig. XI. 6). The deflection of the pointer in this depends on the state of magnetisation of the iron ring, so that if the ends of the ring are parted and the instrument placed in the magnetic field, the pointer will deflect. Although useful for qualitative measurements with strong fields, this instrument is not suitable for accurate measurements or weak fields.

A fluxmeter can be used to measure the change in magnetic flux through a circuit. It consists of a light, freely suspended coil moving in the radial air gap of a permanent magnet. The coil former is non-conducting, so that there is no damping torque. The suspension is a silk thread and the current is led in through fine silver wires coiled in opposition, so that the controlling torque is reduced to a minimum. If the coil is connected to an external circuit in which a magnetic flux is changing, the angular velocity of the coil adjusts itself to such a value that the e.m.f. induced in the coil by its motion in the gap is just equal to the e.m.f. induced by the changing magnetic flux in the external circuit. If the magnetic flux in the external circuit changes in a short time from one value to another, the coil moves through an angle proportional to the change, and to the number of turns in the external circuit. The instrument is calibrated in flux turns and the pointer reading noted immediately before and after the flux change takes place, the difference between the readings being equal to the change of flux turns in the search coil.

Measurement of Power

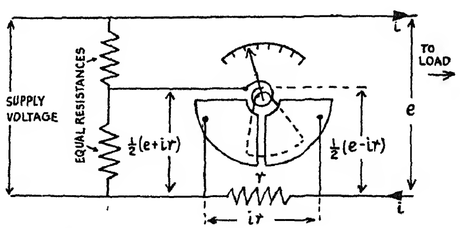


Fig. XI. 8. Connections of electrostatic wattmeter.

The electrostatic wattmeter resembles in construction an electrostatic voltmeter, but the connections are arranged as illustrated in Fig. XI. 8. The vane is attracted to both sets of fixed plates, and the resultant torque is the difference between the forward and reverse torques. Since the attraction between two charged plates is proportional to the square of the voltage between them, one torque is proportional to $\left(\frac{e + ir}{2}\right)^2$ and the other to $\left(\frac{e - ir}{2}\right)^2$, where e is the voltage

across the load, i the current through it, and r the value of the resistance. The resultant torque is therefore proportional to $e\,i\,r$. r is constant, so that the torque is proportional to the $e\,i$ which is the power used in the load. The two equal resistances may be replaced by two equal capacitances or a centre tapped transformer winding may be used. This wattmeter is used for high voltages and for measuring very small powers.

Heavy current standard wattmeters of the dynamometer type have been developed for currents up to 5,000 amperes. One instrument has a "current coil" consisting of two concentric tubes connected together at one end. The current flows in along one tube and out along the other, setting up a magnetic field in the space between them. The voltage is applied to the moving coil which lies in the magnetic field set up by the current. Cooling water may be passed through the inner tube.

Dynamometer wattmeters do not function normally at frequencies above about 5,000 c.p.s. owing to the effects of self capacitances of the windings. For higher frequencies, various valve wattmeters have been devised, one being illustrated in Fig. XI. 9. The valves are exactly similar and connected as square-law voltmeters; the moving coil meter registers the difference between their anode currents. In use, the anode current of both valves increases, but one current increases more than the other, and the difference is proportional to the average product of voltage and current in the load circuit. The limitations to this circuit are the difficulty of ensuring that the operating characteristics of the valves are exactly square law, and that of obtaining suitable transformers to supply the centre tapped input voltage.

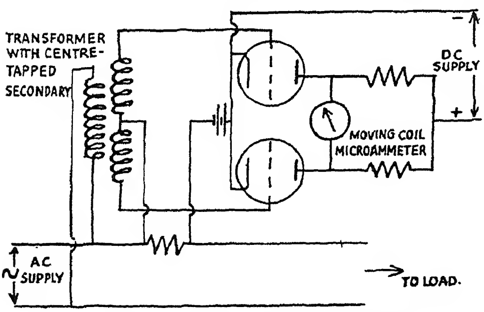


Fig. XI. 9. Circuit of valve-wattmeter.

The Ratiometer

A ratiometer may be used to measure the ratio of two currents, either direct or alternating; it consists of two coils firmly connected together with the planes of the coils at right angles. The whole assembly is freely pivoted in a strong magnetic field provided by a permanent magnet. Very light connecting wires are used so that there is a negligible controlling torque. The coils are so connected that the torques produced by the currents in them act in opposition

and the whole assembly takes up a position such that these opposing torques are equal. The position of the pointer then depends only on the ratio of the currents in the two coils.

In an ohmmeter one coil carries the current flowing in the unknown resistance and the other is connected in series with a known resistance across the supply voltage. The current in the coils is in the same ratio as the two resistances, so that the pointer position depends on the resistance of the unknown but is independent of the supply voltage.

Frequency Measurement

One of the most widely used frequency meters for frequencies between 20 c.p.s. and 10 c.p.s. consists of a series of metal reeds placed near the pole of an electro-magnet, the winding of which carries the alternating current under test. The reeds are attracted to the magnet by an alternating force and so vibrate. They are weighted at the ends and the weight and length of each reed adjusted so that each has a different natural oscillation frequency (marked on the instrument above each reed). Only one reed vibrates strongly, that is, the one which has an oscillation frequency close to the frequency of the alternating force.

For frequencies up to 100,000 c.p.s. use is made of the fact that the impedance of a coil rises and that of a condenser falls as the supply frequency is raised. The current in a coil is rectified and passed through one coil of a ratiometer, while the current in a condenser connected across the same alternating voltage is rectified and passed through the other coil of the ratiometer. The indication of the ratiometer depends on the ratio of the two currents and so changes with frequency. The indications of the meter are not affected by the voltage because this does not affect the ratio of the currents; the reading is, however, dependent on the waveform of the applied voltage.

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CHAPTER XII

SPECIALISED ELECTRICAL

Pyrometers for the electrical measurement of temperature (described in Chapter XV of *Scientific Instruments*) have been employed for many years ; recently many other quantities have been measured by electrical means.

Many of the instruments described in this chapter depend on a measurement of resistance. One of the most usual circuits for this purpose is the Wheatstone bridge (Fig. XII. 1). In this the p.d. between B and C is a fraction of that between A and B, and the same applies to the p.d. between D and B. If the fractions are equal, which occurs when $R_1 : R_2 :: R_3 : R_4$: there is no p.d. between C and D and no current flows in the galvanometer. The bridge is then said to be balanced. If a sensitive galvanometer is used a very small change in one of the resistances will cause a large deflection of the galvanometer pointer. When the bridge is used by adjusting the resistances for a balance, the supply voltage is immaterial.

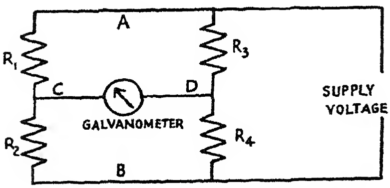

Fig. XII. 1. Wheatstone bridge circuit.

The galvanometer deflection is often used as a measure of the change in one resistance, and the supply voltage must be kept constant if an ordinary galvanometer is used. The necessity for a constant supply voltage in such cases may be obviated by the use of a ratiometer connected with one coil supplied directly from the supply and the other connected as the bridge detector. In this case a change of supply voltage changes the current in both coils in the same proportion and the meter reading is unaffected.

Velocity

The speed of a car or of a moving belt, or the angular velocity of a shaft may be measured by driving either a D.C. generator connected to a moving coil voltmeter, or an A.C. generator connected to a rectifier voltmeter or to a frequency meter.

Air speed may be measured by blowing air past a heated wire and measuring the change of resistance which results from cooling. The resistance is connected to a bridge circuit, and the detector may be calibrated in terms of the velocity of the air. A second, similar,

heated wire in contact with still air is also connected in the bridge, so that a change in the air's temperature affects both and has little effect on the calibration.

An alternating velocity, for example that of a piston, can be measured by attaching to the moving part a permanent magnet, one end of which slides in a coil. The magnetic field cuts the coil and induces in it a voltage which depends on the strength of the magnet and the number of turns of the coil. If the arrangement is correctly designed, the induced voltage at any instant is proportional to the velocity of the magnet. The alternating voltage so produced may be examined with the aid of a cathode ray oscilloscope (afterwards referred to as a C.R.O.), or may be applied to a moving iron voltmeter which will register a voltage proportional to the root-mean-square velocity.

Vibration

The acceleration of a part of a machine may be measured with the aid of a "vibration pick-up". The working part of this is a quartz crystal, one end of which is fixed to the body of the pick-up, the other applied to the machine. The inertia of the system tends to oppose the motion and an alternating force, which is proportional to the alternating acceleration of the machine part, is applied to the crystal. The crystal develops a small e.m.f. between its faces which is proportional to the applied force and, therefore, to the acceleration of the part being examined. The e.m.f. is amplified by a suitable amplifier (a video-frequency amplifier must be used if very rapid changes in acceleration are present) and the amplified voltage examined on a C.R.O. or measured with a voltmeter.

The velocity of the part may be obtained by "integrating" the e.m.f. produced, with a circuit of the type shown in Fig. XII. 2.

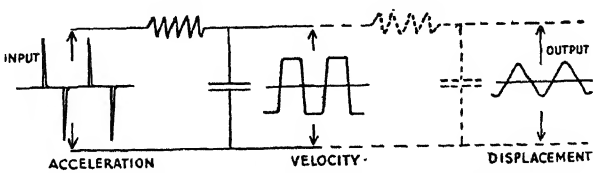

Fig. XII. 2. Illustrating the action of integrating circuits.

The resistance and condenser are made so large that the condenser has no time to charge appreciably during half a cycle of the input e.m.f. The voltage driving current through the resistance is therefore practically equal to the input voltage, so that the current flow into the condenser is proportional to the input e.m.f. But the current flow into a condenser is the rate of change of the charge in it and is proportional to the rate of change of the p.d. across it. Thus the

input e.m.f. is proportional to the rate of change of p.d. across the condenser, or, since acceleration is the rate of change of velocity and the input e.m.f. is proportional to acceleration, the p.d. across the condenser is proportional to the velocity of the moving part.

If the voltage so produced is integrated again by a second similar circuit, a voltage is obtained which is proportional to the displacement of the moving part. With this instrument it is possible to analyse accurately vibration in a machine and to locate the magnitude and cause of individual vibrations.

The Stroboscope

This is an instrument by which a rotating or oscillating object may be made to appear stationary. In its simplest form it consists of a moving shutter rotating in front of a light source. If the speed of the shutter is arranged so that light falls on the object once per revolution or oscillation, the eye sees a succession of pictures all showing the same point in the cycle of movement; persistence of vision causes the eye to receive an impression of a stationary object (with some flicker at speeds below 800 r.p.m.). If the speed of the flashes is slightly too low or too high, the object appears to move slowly forward or back.

The stroboscope may be used to measure the power being transmitted by a rotating shaft. A straight line is marked along the shaft parallel with its axis; when the shaft transmits power it is twisted, and the angle of twist is proportional to the power transmitted divided by the speed. The stroboscope is used to allow the line to be seen and its angle of twist measured; then from a knowledge of the angle and the number of flashes per second from the stroboscope, the transmitted power may be determined.

Most modern stroboscopes use a gas discharge lamp to produce the flash. Such a lamp glows only when the voltage applied to it exceeds a particular value. The lamp is operated from an A.C. supply derived from a valve oscillator. The lamp flashes twice per cycle and the number of flashes per second is varied by changing the frequency of the oscillator. Such stroboscopes may be used to measure speed or to examine the performance of a moving part at speeds between 400 and 10,000 r.p.m.

Length

Displacements of the order of 10^{-5} inch have been measured by an electrical micrometer using the change of resistance of a wire with temperature. Two coils of fine platinum wire are connected in a Wheatstone bridge circuit and the junction of the coils is attached to a lever. A movement of the end of the lever closes up one coil and extends the other. The temperature of the closed coil therefore rises and that of the open coil falls. The resulting changes of

resistance upset the balance of the bridge and a current flows in the galvanometer which may be calibrated in thousandths of an inch displacement at the end of the lever.

Another electrical micrometer consists of two similar iron-cored coils connected in an A.C. bridge circuit with a rectifier instrument as the balance detector (Fig. XII. 3). One coil has a small air gap in the iron circuit which can be varied by a movement of an iron "keeper". The impedance of such a coil decreases rapidly with an increase in the size of the air gap, so that any movement of the keeper unbalances the bridge and a current flows in the detector.

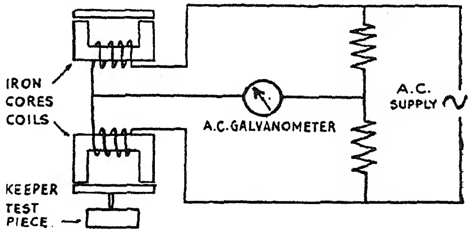

Fig. XII. 3. Electric comparator. Motion of the test piece unbalances the bridge.

The dependence of impedance on air gap thickness is the basis of the magnetic thickness tester used for measuring the thickness of paint on a magnetic surface. The paint provides the "air gap," since magnetically its properties are similar to those of air.

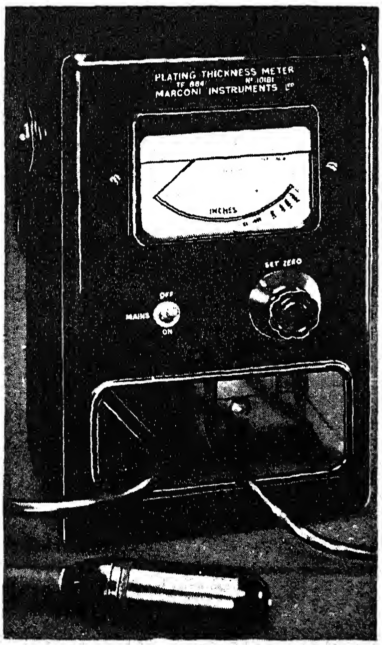

Fig. XII. 4. Commercial magnetic thickness tester.

In another instrument, known as a supersonic depth gauge, the thickness of a plate is measured from one surface by a method similar to that used for depth-sounding. A valve oscillator generates pulses of voltage at a frequency of about 100 kc/sec.; each pulse lasts for about 10^{-4} second and several pulses are produced in each second. The output from the valve oscillator is supplied to a quartz crystal which is held against the surface of the material. The applied voltage causes the crystal to vibrate and set up a supersonic sound wave in the plate. At the same time as the sound pulse is initiated, a single-stroke time base connected to the X (horizontal) plates of a C.R.O. is triggered, and the spot

commences to move across the C.R.O. screen. The pulse is reflected from the bottom of the material and returns to the surface, where a second quartz crystal is made to vibrate and so generate an alternating voltage. This alternating voltage is rectified and applied to the Y (vertical) plates of the C.R.O., so that the trace on the screen shows a vertical displacement. At each pulse the same procedure occurs, so that the motion of the spot on the screen is repeated many times per second, and, owing to persistence of vision, the eye sees a stationary trace. The distance travelled by the spot on the screen before the vertical deflection occurs is a measure of the depth of the material. The apparatus also indicates the position of any flaws, since these produce subsidiary reflections.

Strain

Strain gauges make use of the fact that, when a wire is stretched, its length increases, its cross-section decreases and its resistance rises ; as long as the wire is not over-stressed the change of resistance is proportional to the extension. A strain gauge consists of a grid of extremely fine wire (usually nichrome) attached to two stout paper strips ; the latter are firmly cemented to the specimen under test so that an extension of the specimen stretches all the wires in the grid. The change of resistance of the wires is a measure of the strain (extension per unit length) in the specimen. For steady strains the change of resistance is measured with a Wheatstone bridge ; fluctuating strains are usually measured by passing a steady current through the strain gauge and amplifying the fluctuations of voltage across it by a valve-amplifier. The amplified voltage may be examined with a C.R.O. or measured by a voltmeter.

Moisture Content

The moisture content of absorbent materials such as wood, grain or yarn may be inferred from the resistance or the capacitance offered by a sample of the material between standard electrodes. In a method used for wood, two fine needles, held in a holder to keep them at a constant spacing, are inserted into the specimen and the resistance between them measured. This resistance is closely related to the moisture content of the specimen, and if the test prods are connected in a bridge circuit, the galvanometer can be calibrated in terms of percentage moisture content.

A similar method is used for yarn or cloth specimens, but in this case the test electrodes are flat plates between which the material is placed under pressure. The resistance depends on the moisture content and on the thickness of the specimen.

Capacitance measurements depend on the fact that the capacitance between two electrodes separated by an absorbent material increases enormously when the material absorbs water. The capacitance may

be measured by an A.C. bridge or may be included in the resonant circuit of a valve-oscillator. In the latter case a variable condenser, connected in parallel with the test condenser, is adjusted to keep the oscillator frequency at some predetermined value (for example by combining the output from the oscillator with that from a constant frequency source to produce an audible beat note). The change of capacitance of the variable condenser to compensate for the introduction of the specimen is then a measure of the moisture content. For measurements of this type the specimen may be placed between flat plates or, in the case of grain, in a condenser consisting of two concentric cylinders.

The presence of moisture increases the power loss in the test condenser and this may be measured by a suitable circuit and used as a measure of the moisture content.

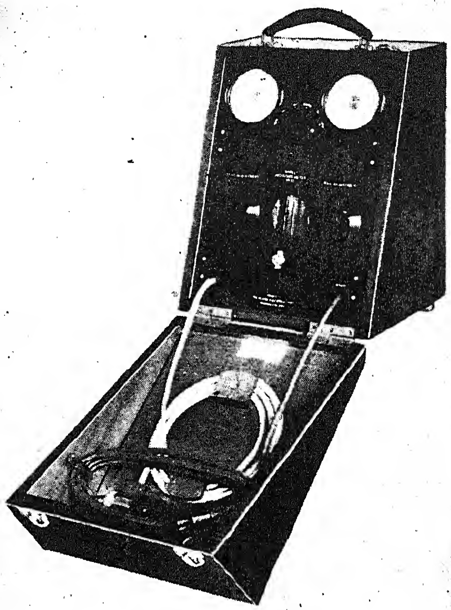

Fig. XII. 5. Shirley moisture meter. Used for textile testing and operated by the resistance of the specimen.

Hygrometry

Although the presence of moisture in air changes the capacitance of an air condenser, the effect, even with high humidities, is too small to be easily measured. Humidity may, however, be measured electrically by measuring the resistance of a moisture absorbent substance such as calcium chloride. A piece of cloth is impregnated with calcium chloride and connected in a suitable circuit which indicates its resistance. The moisture content of the calcium chloride varies in proportion to the humidity of the air and the resistance of the specimen changes accordingly. The indicator used may be calibrated directly in percentage relative humidity.

Acidity (pH value)

Many substances ionise when dissolved in water, i.e., the molecules dissociate into positive and negative ions. Pure water itself is slightly

ionised, containing approximately 10^{-7} gram per litre of positive charged hydrogen ions and an equal amount of negatively charged hydroxyl ions (OH). The addition of an acid increases the proportion of hydrogen to hydroxyl, while the addition of an alkali lowers it. The logarithm of the concentration (with the sign reversed) is known as the pH value. The pH value is a function of the acidity of the solution ; a pH value of 7.07 indicates neutrality; a smaller value indicates acidity and a greater indicates alkalinity. pH values range from —0.3 to 14.5.

The e.m.f. developed between a solution and an electrode immersed in it depends on the hydrogen ion concentration and on the material of the electrode. The pH value of a solution is found by measuring the e.m.f. set up between the electrode in it and the electrode of a calomel half-cell. The latter uses a mixture of calomel and potassium chloride as its electrode, and this is immersed in a saturated solution of potassium chloride. The solution in the test cell makes electrical contact with the potassium chloride through a porous plug which prevents the two solutions from mixing. One standard test electrode is known as a hydrogen electrode and is a preparation such as platinum black, which has been made to absorb a high percentage of hydrogen.

The e.m.f. produced between the test electrode and the calomel half-cell must be measured by a method which requires a negligible current flow. A standard potentiometer may be used with a very sensitive meter or the e.m.f. may be measured by change of anode current of a valve when the e.m.f. is applied in its grid circuit. If a valve is used, it must have an extremely high leakage resistance between the grid and other electrodes, and must have an extremely good vacuum. Triodes suitable for this purpose are known as electrometer triodes ; often the grid is connected to a cap which is fixed to a long glass stem projecting well above the main glass envelope ; this construction is adopted to reduce leakage currents.

Remote Indication (Telemetering)

Several remote indicating systems have been devised to show the value of some quantity such as the level of a liquid, wind direction, etc., on a meter at some distant point. A mechanical displacement of a float or other object is made to change the electrical characteristics of a coil, a condenser, or a resistance, and so cause a current to flow in wires connected to the recording instrument. Capacitance variation is rarely used owing to the difficulty of making large adjustable capacitances.

Resistance Telemetering

Three circuits using resistance variation are illustrated in Fig. XII. 6. In that shown in Fig. XII. 6 (a) the motion of the float

moves a sliding contact along a resistance and so changes its value. The change of resistance changes the current in one coil of the ratiometer and thus changes its deflection. A ratiometer is used so that any change in the supply voltage changes the current in both coils in the same proportion and so does not affect the meter reading. Either direct or alternating voltage may be used. The indications with this circuit are liable to errors due to changes in contact resistances or line resistances.

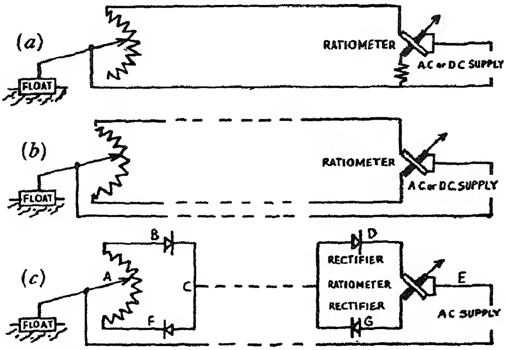

Fig. XII. 6. Telemetering circuits using resistance variation.

In the circuit of Fig. XII. 6 (b) the motion of the float changes the ratio of the currents in the two coils of the ratiometer. Variations of contact resistance or line resistance have less effect than in the previous case, since the resistance in both circuits is changed; it should be noted, however, that adding the same resistance in both arms will affect the ratio of the resistances and so influence the meter reading, except in the special case when the resistances are equal.

The circuit of Fig. XII. 6 (c) requires only two leads to the distant point and so is often preferred. This circuit operates with an A.C. supply and the metal rectifiers cause the current to pass through one circuit (ABCDE) when the voltage acts one way, and through the other (EGCFA) when the voltage reverses. The frequency of reversal is too high for the ratiometer to respond to the variations of current and the meter adjusts itself so that the average forward and reverse torques are equal, that is, it responds to the average current ratio. The performance of the circuit is thus similar to that of the previous circuit.

Inductance Telemetering

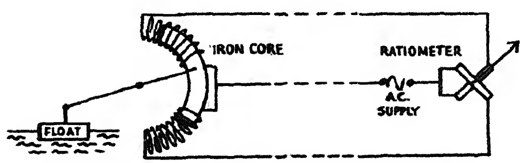

Fig. XII. 7. Telemetering circuit using inductance variation.

Inductance variation is used in the circuit shown in Fig. XII. 7. In this circuit the motion of the float moves an iron core out of one coil into another. The impedance of the coil into which the iron core is pushed, increases, and the

impedance of the other coil decreases, so that the current in one coil of the ratiometer rises and that in the other falls, and the meter deflects. A similar result may be obtained if a copper sleeve is used in place of the iron core. Such a sleeve reduces the impedance of a coil over which it is placed, so that a motion of the sleeve unbalances the circuit and changes the ratio of the currents in the ratiometer.

In another system a motion of the float changes the mutual inductance between two circuits. One circuit carries an alternating current and the other is connected to the remote indicator. The e.m.f. induced in the indicator circuit is proportional to the current in the first circuit and to the mutual inductance between the circuits. The current is kept constant by a special regulator so that the e.m.f. actuating the remote indicator is dependent only on the position of the float.

Selsyn Motor

A remote indicator which is a development of a transformer is known as a Selsyn motor; the arrangement is illustrated in Fig. XII. 8. The transmitter and receiver are identical, each having an iron stator on which are wound coils with their axes 120° apart. An iron rotor, which can revolve freely inside the stator, carries a single winding which is connected through slip rings to an A.C. source. The alternating magnetic flux produced by the rotor cuts the stator coils and induces e.m.f.'s in them. When both rotors are in the same position, relative to their stators, the e.m.f.'s induced in any coil on one machine are exactly equal to those induced in the corresponding coil on the other. The e.m.f.'s act in opposition, so that no current flows in the stator coils. A movement of one rotor changes the e.m.f.'s in the stator coils of that machine, so that the e.m.f.'s are no longer balanced and currents flow in the stator coils. These currents produce an alternating magnetic flux in the stator of the second machine and this reacts with the magnetic flux from the rotor and exerts a torque on it. If the second rotor is free to move it will rotate under the influence of the torque until it reaches a position at which the e.m.f.'s balance, when the stator currents cease and the rotation ends. One rotor is thus a "slave" of the other and any angular displacement of the one results in a similar angular displacement of the other.

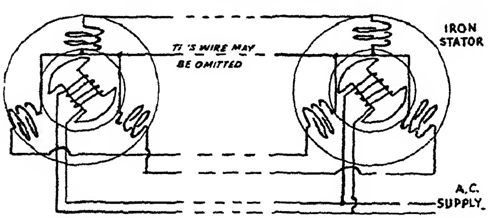

Fig. XII. 8. Connections of Selsyn motors.

The above remote indicating systems may be used to indicate the position of any suitable moving system, as for example a vane showing wind direction.

Servo Techniques

Many forms of remote indication or remote control make use of a servo motor which is a small electric motor sensitive to very small voltages. For example, in one system, the position of a meter pointer is automatically followed. The pointer carries a light aluminium vane and a second pointer carries a small coil. The coil is so placed that, when the two pointers are in line, the vane is half in the coil. The coil is connected in an A.C. bridge, arranged to be balanced when the vane is half in the coil. A movement of the meter pointer changes the impedance of the coil (reduces it if the vane enters the coil to a greater extent) and so unbalances the bridge. The unbalance voltage is arranged to operate the servo motor which is geared to the second pointer and to one of the remote indicators previously described. The motor continues to run, and the second pointer to move, until the bridge is once more balanced. This occurs when the two pointers are once more in line. The remote indicator shows the position of the second pointer and therefore that of the first. This system has the great merit that the original indication is obtained from an instrument which is not loaded and frictional, and other errors are thus reduced to a minimum.

The same performance may be obtained if the second pointer carries a small metal vane instead of a coil. In this case, the capacitance between the two vanes is used as the controlling quantity.

The above principle may be used to stabilise the variable quantity instead of recording its variations. For example, if the "free" pointer indicates the level of fluid in a tank, the second pointer may be fixed at some predetermined position. Change of fluid level changes the position of the free pointer, and so unbalances the control bridge. The servo motor is thus caused to rotate, but in this case it is coupled to the control of a pump motor and causes the latter to pump fluid into or out of the tank until the original level is restored and the free pointer returns to the balance position.

For automatic control purposes, light sensitive cells are used. These are of three types; photoelectric cells containing an anode and a cathode coated with caesium in an evacuated glass bulb—light falling on the cathode causes it to emit electrons at a rate proportional to the light intensity; barrier layer cells formed of a transparent layer of gold on selenium develop an e.m.f. proportional to the light intensity; photo conductive cells formed of a thin layer of selenium have a resistance which decreases as the light intensity increases.

The usual control circuit uses two light cells and the indicator is arranged so that normally both cells are half obscured. A movement of the indicator (for example, the mercury in a thermometer) reduces the light in one cell and increases it on the other, and the resulting unbalance voltage operates a relay or a servo motor which performs the appropriate corrective action.

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SECTION 4

ELECTRONIC INSTRUMENTS

CHAPTER XIII

VALVE CIRCUITS

Many modern measuring instruments use valve circuits as amplifiers, oscillators or relays, and many such circuits are mentioned in other chapters of this book. This chapter is a brief survey of the more important of the many uses of thermionic vacuum valves.

The Diode Rectifier

A diode passes current only from anode to cathode and may be used (Fig. XIII. 1) to rectify an alternating supply to give a D.C. supply. In the circuit of Fig. XIII. 1 the condenser is charged by pulses of current through the diode and discharges continuously, maintaining an almost steady current through the load. The mean output potential difference (p.d.) is just less than the peak value of the alternating voltage. The choke and condensers smooth out fluctuations so that the p.d. is kept almost constant. In the absence of the reservoir condenser the output voltage is lower and fluctuates more, but the circuit can supply heavier load currents without damage to the valve; this occurs because the diode conducts for almost the whole of the alternate half cycles, so that the ratio of load current to peak diode current is greater. Full wave rectifiers using two diodes with a common cathode are more usual. In these the diodes conduct alternately, the output voltage fluctuates less and larger currents can be supplied.

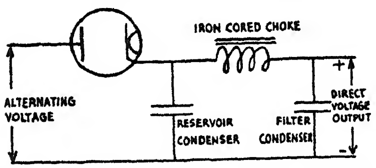

Fig. XIII. 1. Diode rectifier circuit.

Audio Frequency and Video Frequency Amplifiers

The name audio frequency is used to designate the frequencies found in audible sounds, namely, the range 20 c.p.s. to 20,000 c.p.s. The video frequency range is from 20 c.p.s. to about 2,000,000 c.p.s.; these are the frequencies encountered in the signals produced by modern television cameras. To avoid distortion the amplifier must amplify equally well over the whole range (though some falling off in amplification at high or low frequencies is scarcely noticeable) and must not change the wave shape of a voltage being amplified.

Audio frequency amplifiers may use triodes or pentodes; the latter are more often employed in commercial equipment because a higher voltage amplification may be obtained using a single stage.

If triodes are used the anode load is usually a resistance or a specially designed transformer, and a single stage may give an amplification of from 8 to 100 times. Because of the high anode resistance of a pentode it is almost impossible to design a suitable transformer, and resistance anode loads are employed giving a "stage gain" of from 50 to 300 times.

Video frequency amplifiers normally use pentodes because the capacitance between anode and grid of a triode causes effects which become appreciable above about 30,000 c.p.s. and makes normal operation of an amplifier using several triode stages impossible. A small coil is often included in series with the anode load resistance ; its inductance, if correctly chosen, compensates for the effect of the grid-cathode capacitance of the following valve and allows the amplification to be maintained to very high frequencies. However, even when this compensation is included, it is impossible to maintain a very high "stage gain" at the highest frequencies, and generally it is limited to between 5 and 20 times over the whole range.

Voltage amplifiers are normally operated under "class A" conditions, that is, with a steady negative grid voltage such that the superimposed signal voltage neither drives the grid positive nor to the region of characteristic curvature. Under these conditions no power is absorbed by the grid circuit, and there is no distortion.

Audio frequency amplifiers are often required to supply power ; for example, to operate a loudspeaker. For this purpose the load resistance must be neither too high nor too low, and a transformer of suitable ratio is usually employed so that the effective resistance in the anode circuit of the valve is the correct value. The valve used must be large, since 70% to 90% of the D.C. power fed into the anode circuit is wasted as heat at the valve anode ; the remainder is converted into useful output power. Two valves may be used in push-pull, so that as the current in one valve increases that in the other decreases ; this balances out the effect of curvature in the characteristics. "Class B" push-pull is used where economy in power input is desirable ; the negative grid voltage is chosen so that the mean anode current is small and the valves then conduct alternately, each dealing with alternate half cycles of the input.

Radio Frequency Amplifiers

Radio frequency amplifiers (above 20,000 c.p.s.) are usually required to amplify voltages within a comparatively narrow band of frequencies. In some amplifiers the anode load is a coil connected in parallel with a condenser, and has a high impedance at one frequency and a small impedance at higher and lower frequencies. In other amplifiers the resonant properties of a coil and condenser in series are employed ; here the valve is made to induce an alternating voltage in the circuit, and this is magnified by the resonance effect.

In this case, also, the amplification falls off above and below the resonance frequency.

More complex circuits, consisting of two or more tuned circuits coupled together, are also used. Pentode valves are employed in all radio frequency amplifiers used for voltage amplification. (For typical circuits, see Fig. XIII. 2.)

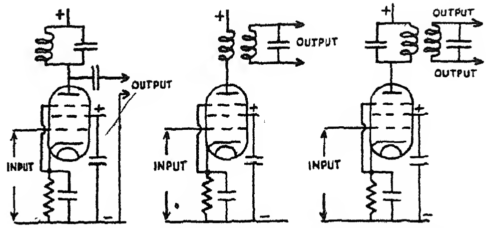

Fig. XIII. 2. Typical R.F. pentode amplifying circuits.

In transmitters and for certain industrial purposes where a source of radio frequency power is needed, a tuned anode circuit is coupled to the load and the valve operated under "Class C" conditions. A heavy negative bias is applied to the grid and a very large alternating input voltage applied. The valve conducts in short pulses, and the pulses of current maintain an oscillation in the anode circuit which is tuned to the frequency of the input voltage. The valve conducts only while the voltage across it is low, and as a result the power wasted at the anode is small—about 80% of the power drawn from the H.T. supply appears as radio frequency power. To obtain the maximum possible output power the input signal is allowed to drive the grid positive and a steady current flows in the grid current as a result of the electrons collected by the grid. The input circuit absorbs power; for a valve delivering 100 watts about 5 watts driving power is required.

Feedback

The performance of an amplifier may be profoundly modified if part of the output voltage is fed back to the input. If the feedback voltage opposes the applied input voltage (negative feedback), then the input voltage must be raised to overcome the feedback voltage and the amplification is reduced. Changes in amplification due to changes in the valves, power supplies, frequency of the input signal, etc., are minimised by corresponding changes in the feedback voltage (providing that the feedback circuit is not affected by frequency). The amplifier is made more stable and inequalities in its frequency response levelled out.

Positive feedback increases the amplification and exaggerates inequalities in the frequency response; "reaction" is positive feedback, and is sometimes used to improve the sensitivity and selectivity of a simple receiver. Unfortunately, positive feedback exaggerates any change in amplification due to changes in the valves or power supplies. If the feedback voltage is sufficient the amplifier will supply the whole of its own input signal and then becomes an oscillator.

Oscillators

A triode oscillator is an amplifier with positive feedback sufficient to supply its own input signal. The frequency of oscillation is that at which the phase of the feedback is correct; the amplitude of oscillation grows until the valve operates for part of each cycle over a low slope characteristic or even ceases to conduct, so that the average amplification is such that the input signal is just sufficient to maintain the output signal. Most oscillators are made to supply their own negative grid voltage, the grid and cathode acting in conjunction with the condenser and grid leak as a rectifier circuit, rectifying the alternating input signal and developing a negative grid bias. A few typical triode oscillators are shown in Fig. XIII. 3. The tuned anode oscillator (Fig. XIII. 3a) provides the feedback voltage by mutual inductance coupling between the anode and grid circuits. It is used for frequencies between 10 kc/s and 30 Mc/s.

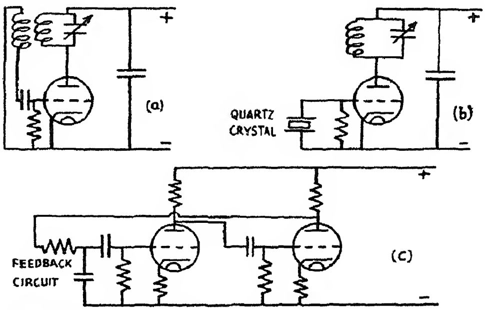

Fig. XIII. 3. Valve oscillators. (a) Tuned anode. (b) Crystal. (c) Resistance capacity coupled.

The quartz crystal oscillator (Fig. XIII. 3b) makes use of the fact that a piece of quartz crystal correctly cut from the mother crystal acts like a parallel tuned circuit with very low losses; the mass of the crystal provides the inductive effect and its elasticity the capacitive effect. The resonant frequency depends on its dimensions and the manner in which it was cut from the crystal. The anode circuit is tuned to a frequency slightly above the resonant frequency of the quartz crystal and acts as a high inductance; in these circumstances the feedback through the anode to grid capacitance is in the correct phase to maintain oscillations. The quartz crystal oscillator can maintain its frequency between very close limits, particularly if care is taken to keep the crystal at a constant temperature. Such oscillators are used for frequencies between about 10 kc/s and 10 Mc/s.

Resistance-capacity coupled oscillators (Fig. XIII. 3c) may be used for frequencies between 0.05 c.p.s. and 100,000 c.p.s. Each valve produces a phase shift of a half-cycle, so that the output voltage from the second is in phase with the input voltage to the first. The feedback circuit is such that at one frequency only the voltage between the output terminals is in phase with that between the input terminals, so that the feedback voltage at this frequency is in the correct phase to maintain oscillations.

The Cavity Magnetron

Of the many oscillators not using triodes, the magnetron is probably the most interesting; it was first described by Hull in 1921. The modern, cavity resonator, form used for generating voltages at frequencies of the order of 10,000 Mc/s consists of a cathode surrounded by a massive, water- or air-cooled, anode in which are drilled cavities opening into the anode-cathode space. A strong magnetic field is maintained parallel with the cathode and the anode made positive to cathode. Electrons emitted from the cathode are attracted to the anode, but are forced to follow roughly spiral paths by the presence of the magnetic field.

As an electron passes the mouth of the cavity it sets up an electro-magnetic disturbance in it, and a wave is sent out down the cavity; this is reflected from the back wall and returns. If conditions are correctly adjusted (correct strength magnetic field and correct H.T. voltage) most of the electrons pass from one cavity to the next at the right time to maintain the wave. The action resembles that of an organ pipe, but instead of a stream of air blowing across the end and maintaining a sound wave in it, a stream of electrons maintains electro-magnetic waves in the cavity.

The Multivibrator (or Relaxation Oscillator)

This is a two-stage resistance-capacity coupled amplifier with the whole of the output fed back to the input (Fig. XIII. 4).

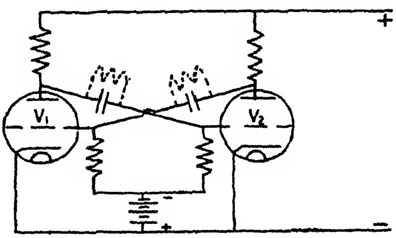

Fig. XIII. 4. Multivibrator circuit. The dotted components are used in the scale of two counter.

Consider an instant after switching on when both valves, V_1 and V_2, conduct normally. The condition is unstable, for if from any cause (such as the random motion of electrons) the anode current of V_1 rises, its anode voltage falls. The change is communicated to the grid of V_2 by the coupling condenser and causes the anode current of V_2 to fall, raising its anode voltage and so driving the grid of V_1 somewhat positive. The anode current of V_1 rises even more, and so on. In a very short time the grid of V_2 is biased heavily negative and V_2 ceases to conduct, remaining non-conducting until the charge which has accumulated in the coupling condenser has leaked away. When the charge leaks away the negative bias on V_2 falls and allows the valve to conduct. The whole procedure then recurs and V_1 ceases to conduct. A roughly rectangular voltage is developed between anode and cathode of either valve. The recurrence frequency of the oscillation is determined mainly by the values of the capacitance and resistances in the grid circuits, but also depends on

the other circuit values. The periodic time of the oscillation is somewhat variable, but it can be made definite by an alternating synchronising voltage applied to one of the grids; for example, a multivibrator with a recurrence frequency of about 50 c.p.s. can be locked by a signal at 500 c.p.s.

The synchronising phenomenon is used in quartz clocks. A quartz crystal oscillator at say 100,000 c.p.s. locks a multivibrator at 10,000 c.p.s. and so on; the last multivibrator is locked at 50 c.p.s. and the output from it used to drive a standard synchronous electric clock. The clock's accuracy is determined by the properties of the quartz crystal and the performance can excel that of any other type of clock.

Electronic Counting

If the coupling condensers in the multivibrator are replaced by suitable resistors and a steady negative bias applied to both, the resulting circuit is stable only when one valve (V_1) conducts heavily and the other (V_2) is non-conducting. If a voltage pulse of short duration is applied to both grids, the circuit "turns over" like a multivibrator but remains in the new state with V_2 conducting and V_1 cut off. Because of its action, the circuit is known as a "flip-flop". The rise of anode current in one valve may be made to generate a voltage pulse to operate a following circuit. The "flip-flop" is a scale of two counter, but it is usually more convenient to count in tens.

One scale of ten counter uses seven valves, the first two being connected as a "flip-flop". The remaining five are connected in a manner based upon the connections of the "flip-flop" with each anode connected through a resistance to each of the other four grids. The "ring of five" so formed has five stable states; in each, one valve only passes no anode current; pulses applied to the grids cause the circuit to pass in turn to each of its stable states. The "flip-flop" passes on alternate pulses to the "ring of five", and an electrically-operated mechanical counting meter connected to the anode circuit of one of the ring valves will respond to every tenth pulse. Indicators are connected in the anode circuit of all the valves, and the total count is found from the reading of the mechanical counter, plus the numbers corresponding to the non-conducting valves. With circuits of this type it is possible to count up to more than 10,000 impulses per second.

The so-called "electronic brain" is a calculating machine using large numbers of electronic counters; because of the high counting speeds which are possible, very involved calculations can be carried out in a short time.

It is sometimes necessary to count only those impulses which are coincident with others. A simple coincidence counter consists of a number of valves with their anodes and cathodes connected

together and sharing a common anode load resistance. The grids are connected separately to the various sources. This circuit is responsive only to voltage pulses which will bias the grids negatively. When a pulse arrives at the grid of a valve the anode current of that valve ceases, but if even one valve still conducts, the potential drop across the anode load resistance scarcely changes and the anode voltage remains low. If, however, all the valves receive a pulse at the same time, the current through the load resistance ceases and the anode potential rises to the full H.T. value. As many valves are used as are required.

Time Base Generators

These are used to provide a voltage (or less usually a current) which varies in a known manner with time. In conjunction with a cathode ray tube a time base may be used to measure time intervals or for a variety of other purposes.

A simple form of time base is shown in Fig. XIII. 5. The condenser charges through the resistance and the p.d. across it rises. Across the condenser is connected a gas-filled triode (a triode valve containing inert gas at very low pressure). The negative voltage on the grid of the valve is sufficient to prevent any electron flow to the anode as long as the anode voltage is below a certain value. When the p.d. across the condenser and valve rises above the critical value, electrons escape past the grid and are accelerated by the electric field between anode and grid. If the anode voltage exceeds about 15 volts the electrons acquire sufficient kinetic energy to dislodge electrons from the atoms of gas with which they collide. The atoms then become ionised, the positive-charged ions (atoms minus some of their electrons) are attracted towards the grid, and the electrons set free are accelerated towards the anode. The fresh electrons, in their turn, produce ions by collision, and at the same time the positive ions collect around the grid and neutralize the effect of its negative charge. Simultaneously, also, a current flows from grid to cathode in the external circuit, and flowing in any resistance in the grid circuit sets up a p.d. which opposes the negative bias voltage. The presence of positive ions neutralizes the space charge near the cathode, so that the valve conducts heavily. (A small resistance is included in the anode circuit to limit the anode current to a safe value.)

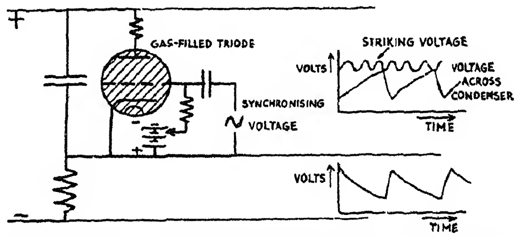

Fig. XIII. 5. "Soft" valve time base. The waveforms illustrate the action.

Thus once the anode voltage exceeds the critical value the valve conducts and discharges the condenser rapidly, and the grid loses control of the anode current. The condenser discharges until the p.d. across the valve falls to about 15 volts, when the electrons no longer acquire the kinetic energy needed for ionisation, the remaining ions re-combine to form neutral atoms, the grid regains control and the valve ceases to conduct. The waveform of voltage produced is illustrated in Fig. XIII. 5.

The recurrence period is rather indefinite, but the circuit may be synchronised by an alternating voltage superimposed on the steady grid voltage. This alternately raises and lowers the grid voltage and so lowers and raises the critical anode voltage, thus determining precisely the time at which the valve "strikes" (Fig. XIII. 5).

The voltage across the condenser rises exponentially, that is, at a continuously decreasing rate. This is because the rate of rise of voltage is directly proportional to the current flowing into the condenser, and as the condenser charges, the p.d. available to drive the current through the resistance decreases.

The fact that the anode current of a pentode is almost independent of the anode to cathode voltage over a wide range is used to provide a linear time base. The anode-cathode circuit of a pentode is used in place of the resistance so that the condenser charging current is almost constant and the voltage across the condenser rises at a constant rate. This rate of rise may be controlled by varying either the screen or grid voltage of the pentode (fine control), or by the substitution of different capacitance condensers (coarse control). The total rise of voltage across the condenser (amplitude) is controlled by adjustment of the negative bias on the grid of the gas-filled triode.

The gas-filled triode will not function satisfactorily with recurrence frequencies exceeding about 15,000 c.p.s.; for higher frequencies a circuit using vacuum tubes is usually employed (Fig. XIII. 6). In this, the condenser charges through the pentode V_1 and is discharged through V_2 when the p.d. across it rises above a value determined by the magnitude of the p.d. across the amplitude control resistance. When the p.d. across the condenser is small, V_2 passes no current, since its anode to cathode voltage is low, and its grid is connected to the anode of V_3, and is many volts negative to the cathode of V_2.

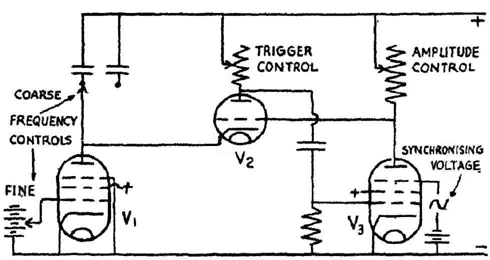

Fig. XIII. 6. Puckle's hard valve time base.

As the condenser charges; the cathode potential of V_2 becomes less positive, so that its anode-cathode voltage rises and its negative grid-cathode bias falls until a point is reached when V_2 conducts. The circuit then "turns over" like a multivibrator and V_2 conducts heavily. The circuit values are so chosen that the condenser discharges to a low voltage when the fall of anode current in V_2 causes the circuit again to turn over, so that V_2 becomes non-conducting. The circuit of V_2 coupled to V_3 replaces the gas-filled triode in the circuit previously described.

The above circuits provide a recurrent time base; for purposes such as Radar, single-stroke time bases are used in which the time base makes one stroke each time an initiating pulse is provided. One of many such time bases is shown in Fig. XIII. 7. A large positive voltage pulse is applied to the input and drives the grid of the valve positive. Electrons are collected by the grid and a large charge accumulates on C_1 which becomes charged to a p.d. almost equal to the peak value of the pulse. When the pulse ends, the valve is biased negatively by the p.d. across C_1 and ceases to conduct. C_1 discharges slowly through R_1, and for an appreciable time the valve remains non-conducting. During this time the condenser C charges through R developing an exponential time base voltage across C. When the valve once more conducts, C discharges, and the p.d. across it remains at a low value until the arrival of the next initiating pulse.

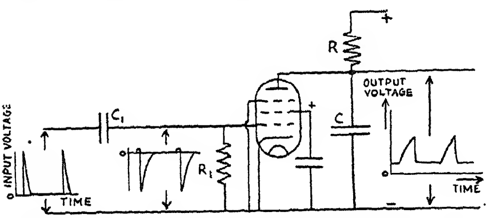

Fig. XIII. 7. Single stroke time base with waveforms showing the operation.

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CHAPTER XIV

CATHODE RAY TUBE APPLICATIONS

The Cathode Ray Oscilloscope

A Cathode ray oscilloscope (C.R.O.) is an arrangement to produce a visual record of the relationship between two quantities, for example, voltage and time. An oscillograph produces a printed record; the terms oscilloscope and oscillograph are, however, often used as synonyms.

A C.R.O. is an assembly of a cathode ray tube (C.R.T.) (described in *Scientific Instruments*, Chapter XXIX) with a low voltage supply for heating the cathode and a high voltage D.C. supply to accelerate the electrons; in addition, most C.R.O.'s incorporate a time base generator (see Chapter XIII), and in some cases a valve amplifier is included. The usual laboratory C.R.O. uses a tube about 6″ in

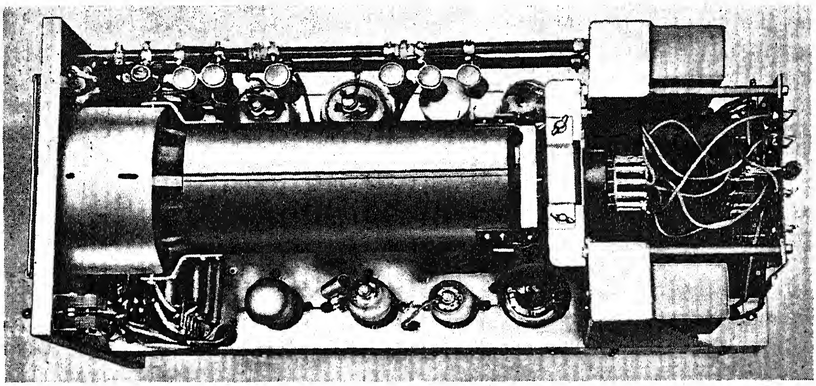

Fig. XIV. 1. Plan view of commercial C.R.O. with double beam tube and amplifiers.

diameter and is operated from A.C. mains. The cathode heater is supplied from a low voltage winding on a transformer, and an accelerating voltage of about 2,000 volts D.C. is obtained from a high voltage A.C. winding used with a diode rectifier (see Chapter XIII).

"Electrostatic" tubes are usually used in modern equipment; in these, the electron beam may be deflected horizontally by a p.d. applied between a pair of plates known as the X plates, or vertically by a p.d. between a second pair of plates—the Y plates. The deflection produced is roughly proportional to the applied p.d.

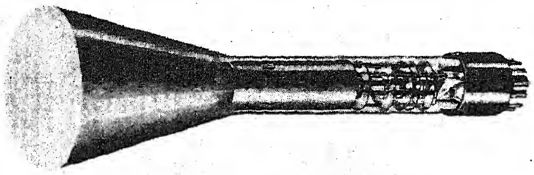

Fig. XIV. 2. Electrostatic cathode ray tube.

In most laboratory tubes one X plate and one Y plate are connected to the final anode and earthed to the chassis of the oscilloscope. This construction is usually convenient, but in a few circuits it necessitates connections which cause the desired picture to appear "upside down" or "back to front" (see "voltage-current characteristics").

The C.R.O. as a Voltmeter

A C.R.O. makes a very useful voltmeter. If a steady p.d. is applied between one pair of deflecting plates the spot on the screen is displaced by an amount which depends on the p.d. and on the sensitivity of the tube. With the usual laboratory tube the sensitivity is of the order of 10 volts per cm. If an alternating p.d. is applied to the deflecting plates the spot oscillates about its mean position, and if the frequency of oscillation is more than about 10 c.p.s. persistence of vision causes the trace to appear as a continuous line with a length proportional to the peak to peak value of the alternating voltage. The tube takes a negligible current from the source of the p.d. (in most oscilloscopes a resistance of about one megohm is connected between the deflecting plates), and the sensitivity is little affected by frequency. At frequencies above about 15 mc/sec., however, resonance in the inductance and capacitance of the leads to the deflecting plates may alter both the input impedance and the sensitivity.

Measurement of Voltage-Current Characteristics

The relation between the p.d. across a circuit and the current flow through it may be found by the method illustrated in Fig. XIV. 3.

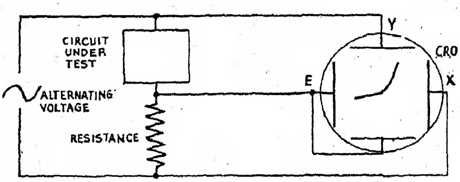

Fig. XIV. 3. Circuit for obtaining voltage-current cyclogram.

The circuit under test is connected in series with a resistance across an alternating voltage, so that at any instant the same current flows through the circuit and the resistance. The p.d. across a resistance is proportional to the current flowing through

it, so that in this case the p.d. across the resistance, at any instant, is proportional to the current flowing through the circuit. The p.d. across the circuit is applied to the Y plates and the p.d. across the resistance to the X plates, so that at any instant the electron beam is deflected vertically by an amount proportional to the p.d. across the circuit and horizontally by an amount proportional to the current flowing through the circuit, and the spot on the C.R.T. screen traces out a line showing how the current and voltage are related.

In the circuit illustrated, the left X plate (viewed from in front of the screen) and lower Y plate are connected to a common point. These connections result in the spot moving up and to the left as the p.d. across the circuit and the current through it increase, so that the positive direction of current in the trace on the screen is from left to right, which is the reverse of the conventional direction.

If the p.d.'s available are too small to produce a reasonable deflection on the screen, valve amplifiers may be used. An amplifier with an odd number of stages produces inverted copy of the input signal, so that by correct choice of amplifiers the trace may be arranged with the conventional axes.

In a reactive circuit, that is, one which possesses an electric field when a p.d. is applied across it or one which possesses a magnetic field when a current flows in it, the effect of the electric or magnetic field produces a phase difference between voltage and current, so that they do not pass through zero at the same instant. If such a circuit is measured in the manner described above the trace will be looped. If the applied p.d. varies with time in a manner given by $e = K \sin pt$ where K and p are constants, the loop is an ellipse. The impedance of such a circuit is defined as the ratio of the peak voltage to peak current and this may be found from the horizontal and vertical dimensions of the ellipse.

If the circuit is purely reactive (for example a loss-free condenser) the trace is an ellipse with its major and minor axes vertical or horizontal, and by correct choice of resistance, capacitance or supply frequency the trace may be made circular.

If the resistance and the circuit of Fig. XIV. 3 are replaced by two similar objects (e.g., two coils) the p.d.'s across them will always be equal and the trace will be a straight line inclined from lower right to upper left at an angle which will depend on the relative X and Y sensitivities. If a line is drawn on the screen the arrangement may be used for the rapid comparison of a number of objects with a standard.

Wattmeter

If the resistance in the circuit of Fig. XIV. 3 is replaced by a condenser with negligible losses and a sinusoidal supply voltage is used, the trace on the screen will in general be an ellipse. It may

be shown that the area of the ellipse is proportional to the power absorbed in the circuit. It is difficult to make accurate power measurements with this circuit, but providing that the capacitance, the deflection sensitivities of the tube and the supply frequency can be accurately measured and that a perfectly sinusoidal supply voltage is available, the method is useful when the power factor (watts divided by volt-amps) of the load is small, or when the supply frequency exceeds about 1,000 c.p.s.

Cyclograms

The type of trace obtained with the circuit of Fig. XIV. 3 is known as a cyclogram. Cyclograms may be used to show the relationship between any two quantities providing that voltages (or currents) may be produced which are proportional to the quantities to be compared. The limitations of this method are mainly due to the difficulty of generating the required voltages and to the fact that the quantities must repeat cyclically if a continuous trace is to be shown on the screen. The latter difficulty may be obviated if a suitable tube is employed and a single trace is photographically recorded.

For example, if it is desired to examine the relation between the speed of a moving position and the strain in the crankshaft, two circuits must be used ; one to generate a voltage proportional to the piston speed, the other to generate a voltage proportional to the strain in the crankshaft. The former may be obtained by coupling a magnet to the crankshaft so that its motion is similar to that of the piston and arranging a coil to be cut by the magnetic flux ; the e.m.f. induced in the coil is proportional to the rate at which the magnetic flux cuts it. A strain-gauge cemented to the crankshaft may be used as described in Chapter XII to generate a voltage proportional to the strain. The two voltages may be amplified by suitable amplifiers (these must not distort or cause a relative phase displacement) and applied to the appropriate deflecting plates.

B—H Characteristics

The magnetic properties of a material may be shown on a cyclogram (Fig. XIV. 4). The material, in the form of a closed ring, carries two windings, one wound evenly around the core and carrying the magnetizing current, the other linked by the changing magnetic flux in the core and an e.m.f. induced in it. The magnetic field strength (H) is proportional

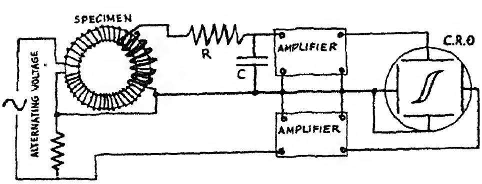

Fig. XIV. 4. Measurement of the magnetic characteristics of iron.

to the current in the magnetizing coil, and a p.d. proportional to this current is developed across the resistance in series with this coil and applied to the X plates (if necessary through an amplifier). The horizontal displacement of the spot from the centre is thus proportional to H. The e.m.f. induced in the second coil is proportional to the rate of change of flux in the core; this e.m.f. is integrated, as described in Chapter XII, by the integrating circuit (RC) and is applied through an amplifier to the Y plates. The vertical deflection is thus proportional to the flux, and therefore the flux density (B) in the core. The whole trace then shows the hysteresis loop of the specimen. Difficulties encountered in this measurement result from eddy currents in the core if the laminations are too thick, self capacitances in both coils, phase shifts or distortion in the amplifier, or imperfect integration. Both the resistance and capacitance of the integrating circuit should be as large as possible.

Engine Indicator

An engine indicator shows how the pressure in a cylinder varies during the stroke; most mechanical indicators suffer from errors due to inertia of the moving parts and, at best, interfere with the shape and volume of the space between the piston and cyclinder head. A quartz crystal can be used to generate a voltage proportional to the pressure in the cylinder, and, since it may be recessed into the cylinder head, need not affect the clearance space. The usual form of indicator diagram shows pressure plotted against piston displacement; a similarly shaped cyclogram may be obtained if the voltage from the crystal is amplified and applied to the Y plates and a voltage proportional to the piston displacement is applied to the X plates.

Several methods are available to generate the X voltage. The simplest is to connect the crank to a sliding contact on a resistance through which a steady current flows; the resistance and thus the p.d. across it then vary with displacement of the piston. This arrangement is not good mechanically because of the wear on the sliding contact. Another, more usual, method is to drive an A.C. generator from the crankshaft. If the generated e.m.f. has the correct waveform and phase, its magnitude is proportional to the piston displacement. The phase of the e.m.f. is correct if the generator is so positioned that its e.m.f. is zero when the piston is at either end of its stroke.

Examination of Voltage Waveforms

The voltage to be examined is applied to the Y plates and a saw-tooth voltage of suitable frequency is applied to the X plates (Fig. XIV. 5); the saw-tooth voltage is obtained from a time base generator of the type described in Chapter XIII. If the time base frequency is an exact submultiple of the frequency of the voltage being examined,

the spot moves steadily from left to right, while the vertical deflection varies in proportion to the signal voltage, until, at the end of one cycle of the saw-tooth voltage, the spot flies back rapidly to the left and retraces the same pattern, which thus appears continuous and stationary.

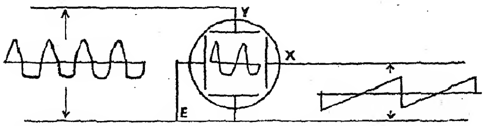

Fig. XIV. 5. Connections of C.R.O. for depicting waveforms.

If the voltage produced by the time base rises at a constant rate (a linear time base), the displacement produced by it is proportional to the time from the commencement of the cycle, and the trace shown on the screen is a graph of voltage against time.

In one form of cathode ray tube made by Cossor, an earthed plate is placed midway between the two Y plates and the latter connected externally to terminals marked Y_1 and Y_2. The beam is split into two; one beam passes between the earth and Y_1 plates and the other between the earth and Y_2 plates. Two spots are thrown on the screen and they may be moved independently in the Y direction, but move together in the X direction. This tube may be used to examine two voltage waveforms simultaneously. One small disadvantage is that one picture is inverted, since if both Y plates are made positive to earth one spot moves up and the other down.

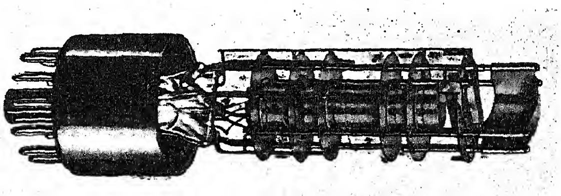

Fig. XIV. 6. Electrode system of double beam cathode ray tube.

Bridge Detector

A C.R.O. in conjunction with a suitable amplifier can detect signals of the order of 10^{-4} volt and may be used as a convenient detector in an A.C. bridge circuit. The amplified signal may be applied to the Y plates so as to produce a vertical line, and the bridge balance adjusted to give the minimum length of line. A more convenient method is to apply the signal to the Y plates and at the same time to apply to the X plates a voltage of the same frequency as the bridge supply. The trace then appears as a tilted ellipse, and the bridge is balanced when the trace is a horizontal straight

line. In an A.C. bridge, two balance adjustments are needed ; one affects the phase and the other the magnitude of the voltage across one arm of the bridge. By suitable adjustment of the phase of the X voltage it may be arranged that the tilt of the line is controlled by one balance adjustment and the opening of the ellipse by the other. Thus the detector indicates the lack of balance and also shows which adjustment is needed.

A double beam tube, with both Y plates connected together to the amplified voltage, shows two parallel straight lines at balance ; as the balance is distorted the lines tilt in opposite directions and/or open into ellipses. If the controls are set so that the separation between the lines is small, the balance adjustment may be made with great accuracy.

In some bridge circuits the balance adjustment depends on frequency and if a non-sinusoidal supply is used the balance adjustment can only remove one component of the input voltage. In such cases the out of balance voltage may be examined with the aid of a normal time base and the correct balance point determined from the appearance of the waveform. For example, if the supply is 400 c.p.s. with a component of 800 c.p.s., the 400 c.p.s. balance point is obtained when the trace shows only an 800 c.p.s. voltage.

Measurement of Time or Frequency

A linear time base with known constants may be used to measure time intervals, but it is more usual to calibrate such a time base against a standard frequency source provided by a quartz crystal oscillator. If a voltage from the oscillator is applied to the Y plates and the time base voltage to the X plates, and the latter adjusted to give a stationary trace, the horizontal distance between similar points (e.g., peak values) on the wave corresponds to the time of one cycle.

The calibrating voltage from the standard frequency source may be applied to the "grid" of the C.R.T., so as to cause the brightness of the spot to fluctuate. This method has the advantage that another voltage may simultaneously be applied to the Y plates for examination ; intervals of one cycle of the standard are marked by bright spots on the trace.

A "null" method is often

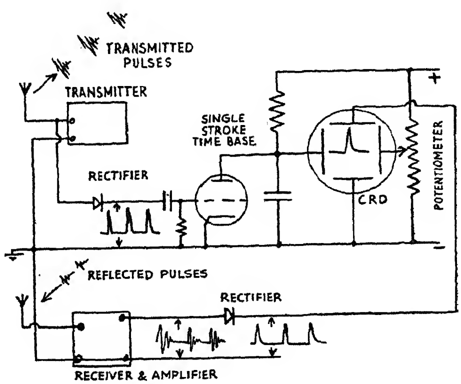

Fig. XIV. 7. Illustrating the principles involved in range measurement with a C.R.O.

used to avoid the difficulty of making accurate measurements on a small screen. For example, in one form of radar an oscillator, at a frequency of several hundred megacycles per second, is arranged to oscillate for about one microsecond at intervals of one-thousandth of a second. The oscillator is coupled to an aerial and radiates an electromagnetic wave, and at the same time triggers a single-stroke time base (Fig. XIV. 7). The wave reflected from an aircraft is received, amplified, rectified and applied to the Y plates of the C.R.T., producing a vertical displacement of short duration. One X plate of the C.R.T. is connected to the output of the time base and the other to the slider of a potentiometer connected across the D.C. supply to the time base. The slider is manipulated until the vertical "blip" coincides with a hair-line across the screen. Under these conditions the p.d. across the tapped portion of the potentiometer is the same as that across the condenser of the time base, and the potentiometer may be calibrated in microseconds or in yards between the transmitter and the aircraft. Slow changes in the D.C. supply do not affect the readings, since both the supply to the potentiometer and that to the time base change by the same amount.

The frequency of two sources may be compared by applying one to the Y plates and the other to the X plates, and adjusting the frequency of one to give a stationary pattern. The spot then traces out a Lissajou's figure, the exact appearance of which depends upon the phase relation between the two voltages. The spot is moved both up and down and from left to right, and the ratio of the frequencies is the ratio of the number of vertical peaks to horizontal peaks in the pattern (Fig. XIV. 8).

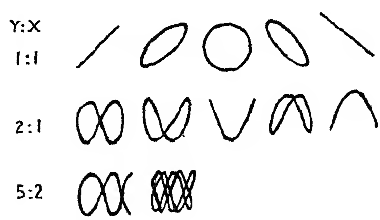

Fig. XIV. 8. Typical Lissajou's figures. The numbers show the relations of Y to X frequencies.

In some uses it is more convenient to measure time intervals by direct measurement on the screen, and for such purposes a circular or spiral time base is used. A circular time base is obtained by the use of the circuit of Fig. XIV. 3 with the circuit replaced by a condenser of suitable capacitance. The spot then makes one circle per cycle of the A.C. supply and moves with a constant angular velocity about the centre. The waveform to be examined may be superimposed on the steady final anode voltage of the tube; this changes the accelerating voltage and so changes the deflection sensitivity of the tube, causing the circle to change in diameter. With this method the wave appears as a radial displacement of the circle, but a large signal voltage is needed to produce any appreciable displacement. If only a small signal voltage is available it may be

applied to the grid of the tube to show bright and dark points on the circle.

A spiral time base may be obtained in several ways. In one method a circular time base is used, but at the same time a saw-tooth voltage is superimposed on the steady accelerating voltage. As the accelerating voltage decreases, the diameter of the circular trace increases, and vice versa. The frequency of the A.C. source is adjusted to an exact multiple (e.g. eight times), the frequency of the saw-tooth voltage, so that the spot makes eight complete revolutions of steadily changing radius, then jumps back to the starting point and repeats its motion. In this way the effective trace length may be made many feet long (or several thousand degrees); the angular movement of the spot being a measure of the time interval.

Picture Reproduction

A picture to be reproduced on a C.R.T. is "scanned" so as to produce a voltage waveform which depends on the light values of a strip of the picture. In modern apparatus this is done in a television camera, but a method now obsolete is similar in principle and easier to understand. A bright spot of light is thrown upon the object and moved downwards and slightly to the right at a constant speed; it then flies back rapidly to the top of the object and repeats the motion so that eventually the whole object is scanned in a series of lines. The whole procedure is then repeated; in modern work about 400 lines, 25 times per second.

The light reflected from the object is picked up by a photo-electric cell which generates a voltage proportional to the light falling on it, so that the output voltage varies with the light and shade in the picture. This voltage is amplified by a suitable amplifier and via a radio link applied to the grid of the C.R.T., so that the brightness of the spot is varied.

Saw-tooth voltages are applied to both X and Y plates; that applied to the Y plates is synchronised by signals sent during the flyback time, so that the spot on the screen moves down at the same proportional rate as the spot of light on the transmitter; that applied to the X plates is synchronised with the transmitter mechanism which moves the spot from left to right. Thus the spot on the C.R.T. screen copies the motion of the spot of light at the transmitter and at the same time the brightness of the spot on the screen varies in the same fashion as the reflected light from the object, and the picture is reproduced on the screen.

A similar principle is employed in the radar apparatus by means of which a rough picture of the terrain below is shown on a C.R.T. in an aircraft. A narrow beam of short wave (about 3 cm. wave-length) radiation is emitted from an aerial; the beam is swung from side to side and the spot on the C.R.T. follows a similar motion.

The strength of the reflected radiation depends on the object from which it is reflected, and the reflected signal is picked up, rectified and amplified, and used to vary the brightness of the spot on the C.R.T. screen. Thus as the beam swings, say from the sea across a coastline, the spot makes a corresponding motion and at the same time varies in brightness. The beam is swung to and fro and the plane of the swing rotated so that it scans the whole terrain, and a corresponding picture, somewhat lacking in detail, is produced on the C.R.T.

Precautions in the Use of Cathode Ray Oscilloscopes

The C.R.O. is such a useful tool that it is sometimes used in cases where other methods are preferable. Although in most cases the capacity current taken by the deflector plates is negligible, it may be important in certain circumstances. For example, the performance of a radio frequency amplifying stage usually depends critically upon the values of the circuit capacitances and the connection of a C.R.O. across such a circuit may materially affect its operation. Thus it may occur that the performance is good with the C.R.O. connected and bad when it is disconnected, or vice-versa.

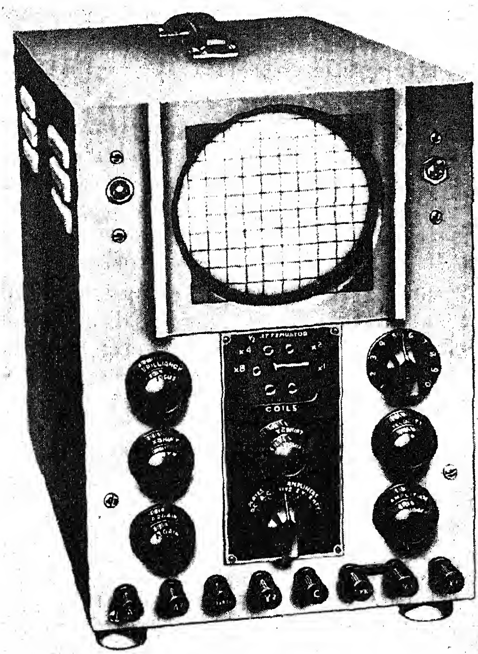

Fig. XIV. 9. Control panel of C.R.O. with electrostatic double beam tube; deflecting coils are also included.

At low frequencies the most usual causes of trouble are stray magnetic and electric fields. Tubes are usually screened to avoid such effects, but the screening is not perfect and a near-by coil carrying a large current may affect the trace; a looped trace, when using a supposedly linear time base, may be caused by the presence of such a stray field. A misleading trace may be caused by capacitance between

supply mains and long leads attached to the Y plate of the C.R.O. particularly when examining the voltage across a high impedance circuit. Other sources of error are an excessive synchronising signal causing the time base voltage to be non-linear, or capacitance between the X and Y plates, or leads attached to them.

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CHAPTER XV

X-RAY APPLICATIONS

When Röntgen discovered in 1895 that a photographic plate was fogged, although wrapped up and in a drawer, by the mysterious radiation, the use of X-rays for "seeing through" solid objects was fairly obvious, depending as it does on the high penetrating power, with different absorption by different substances, and the effect of X-rays on the photographic emulsion. The two main applications of the method are in medical diagnosis and as a method of non-destructive testing in industry.

It was not for some time after their discovery that the nature of X-rays was established. Early attempts to diffract them, which should be possible if they are electromagnetic waves, failed (because of the extremely short wavelength), but in 1912 von Laue suggested the use of a crystal to obtain a diffraction pattern from X-rays, since he calculated that the inter-atomic distances in crystals were of the same order as the estimated wavelength of X-rays (about 10^{-8} cm., i.e. one angstrom unit). The experiment not only established that the atoms in a crystal are arranged in a regular pattern—as in a three-dimensional diffraction grating—but made it possible to measure the wavelength of the electromagnetic waves. This discovery led to the use of X-rays as a very powerful tool in the investigation of the structure of solids, since a very large proportion of solid substances are either crystalline or have their atoms arranged in a partly ordered state, so that X-ray diffraction can be used to explore their structure.

Radiotherapy, the third main application, depends on the biological effects of X-rays. It was found that many of the early research workers, since they did not realise the need for protection, received terrible burns and suffered other serious ill effects such as anaemia. The destruction of living cells by the rays has now been turned to a useful purpose by allowing them to destroy malignant growths, while the rest of the patient's body is protected and the dosage carefully controlled.

Generation and Properties of X-rays

X-rays are generated when high speed electrons are stopped by atoms. The essentials of an X-ray tube are an evacuated chamber with two electrodes across which a high potential difference is applied. The chamber has one or more windows to let out the X-rays emitted from the anode or target, made of Lindemann glass or, in low voltage tubes, aluminium foil, or, better still, beryllium, because at low voltages absorption by the window is important. In early tubes the

residual gases were ionised by the small electron emission from the cold cathode and the electrons produced by the ionisation provided the bulk of the cathode stream. In the more modern hot cathode tube the electrons are provided by an incandescent tungsten filament which forms the cathode and they are focused to a spot on the target.

The "quality" of the radiation depends on the speed of the electrons (i.e. on the accelerating voltage applied to the tube) and on the nature of the target. The X-ray spectrum consists of a background of "white" radiation with a continuous range of wavelength on which is superposed a series of monochromatic lines, characteristic of the target metal. An increase in voltage displaces the "white" background to the shorter wavelength end of the spectrum. These shorter wavelength X-rays are more penetrating and are termed "hard" radiation. The wavelength of the characteristic lines depends only on the atomic number of the target metal. It is these monochromatic lines which are most important in crystallography, the "white" background being used in radiology. A typical X-ray spectrum is given in Fig. XV. 1.

The absorption of X-rays increases with the atomic number of the absorber and, for a given absorber, varies with the wavelength, being greater for longer wavelengths, but having a series of "absorption edges" where the absorption coefficient suddenly increases with decrease in wavelength. This property is used to select a single characteristic line

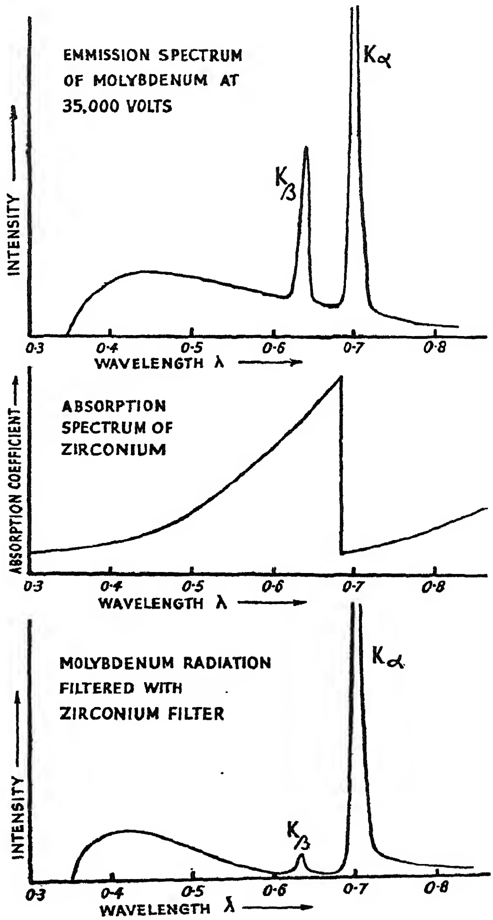


Fig. XV. 1. Emission and absorption spectra illustrating the use of a β-filter.

from the spectrum for crystallographic work. There are two lines, K_α and K_β, fairly close together (see Fig. XV. 1) in the spectrum (actually K_α is a doublet) and it is often an advantage to remove most of the weaker K_β line while leaving the K_α line comparatively strong. This is achieved by using a thin "filter" of another material, whose absorption edge happens to lie between the K_α and K_β wavelengths. This is illustrated in Fig. XV. 1. The "white" radiation is also absorbed to a greater extent than the K_α line.

The efficiency of the tube in generating X-rays is only about 2%, the major part of the energy being dissipated as heat at the anode, which is therefore usually cooled. The method of cooling depends on the type of tube and on the electrical circuit. Some crystallographic and radiotherapy tubes are demountable, i.e. the vacuum can be broken and various parts, e.g. filament and target (anode), can be replaced. Such tubes are continuously pumped and the anode is usually water-cooled. In this case it is necessary of course to earth the anode and have the cathode at a high negative potential. These tubes have the advantage that the target metal can be changed easily (this is an advantage in crystallographic work) and the filament can be replaced at small cost when it burns out. Fig. XV. 2 shows a schematic diagram of a water-cooled demountable tube with its

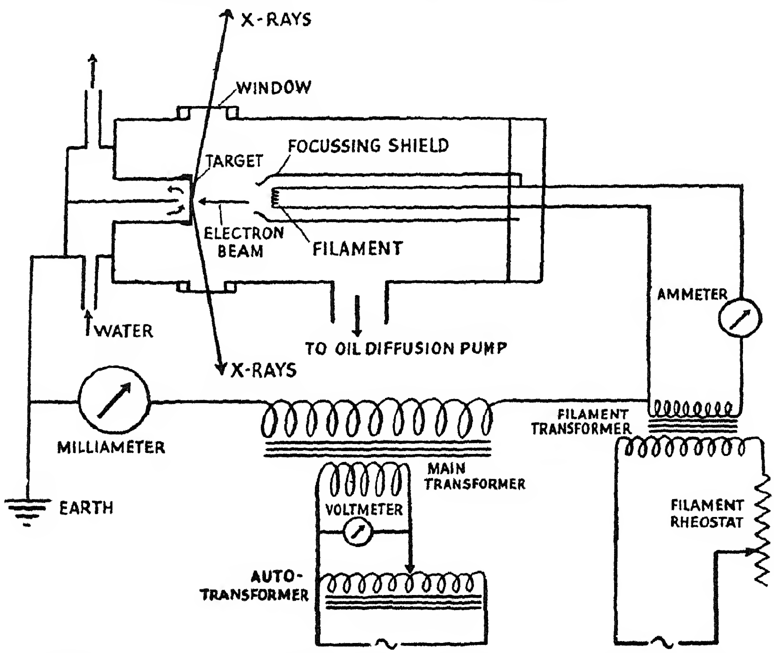


Fig. XV. 2. Schematic diagram of a demountable, self-rectifying hot cathode tube with two windows, with its electrical supply circuits.

electrical connections. It is self-rectifying as is common in this type.

Higher efficiency is obtained by rectifying circuits which are usually used with higher voltage tubes. Sealed-off tubes, on the other hand, last only as long as their filaments, but do not require pumping equipment. Crystallographic sealed-off tubes are usually water-cooled, but for radiography they are often air-cooled (the anode usually has a number of large copper vanes outside the tube, which may be cooled by a fan), or, for more powerful ones, oil-cooled. This is because it is an advantage from the point of view of electrical insulation to have the two electrodes at equal potentials of opposite sign so that the maximum potential difference from earth is half that in the case where the anode is earthed. In oil-cooled tubes, the oil (an electrical insulator) is continuously circulated by means of a pump in a closed system passing through the anode and is itself cooled by water as it passes through the pump. The oil usually circulates round the outside of the glass tube as well.

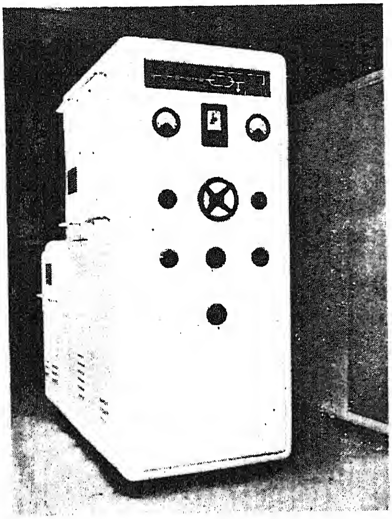
Tube Design

The design of sealed-off tubes used in radiography depends on whether they are to be used for medical or industrial purposes. Medical tubes are usually air-cooled, since the voltages required are not high (usually less than 100 kV.), and designed to take a high current (of the order of 100 mA.) for a short time (so that the patient does not move during the exposure), while industrial radiographic tubes run at lower currents (about 10 or 15 mA.) since short exposure time is less important. Much higher voltages are used in industrial work since it is the voltage which puts an upper limit to the thickness of the objects which can be examined. 100, 200, and 400 kV. tubes are commonly used (200 kV. tubes can be used for light alloys up to several inches thick or for steel up to about 2 in.) and tubes operating at 2 and 3 million volts have been constructed. These very high voltage tubes are usually used for "deep therapy" to replace radio-active substances. For radiography and radiotherapy, tungsten targets are used because of their high melting point. The voltages used on crystallographic tubes are between 25 and 100 kV., the voltage depending on the target metal.

Higher output can be obtained by using a rotating anode so that the focal spot in effect moves over the surface and the heating is less localised. The main difficulty in this type is the making of a vacuum seal through which the rotation can be transmitted.

Industrial Radiography

In this very important method of non-destructive testing the X-ray beam from the focus of the tube passes through the object under examination and the shadow of the object is received either on a film in a light-tight envelope or in a cassette placed close behind the object, or on a fluorescent screen which is viewed through a



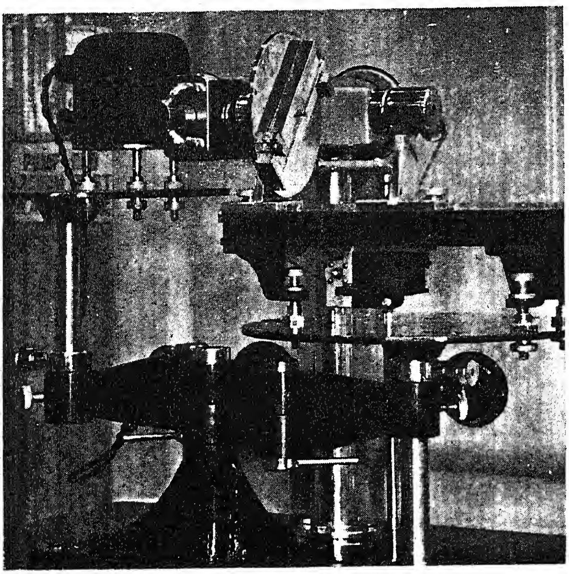


Fig. XV. 3. Metropolitan-Vickers demountable crystallographic X-ray unit. (*Upper*) the control panel. (*Lower*) details of the X-ray tube and its mounting showing the X-ray diffraction cameras in position. The tube itself is the horizontal member at the top of the picture.

mirror (for protection). The differential absorption in different parts of the specimen makes it possible to detect defects such as cracks, inclusions and porosity in castings and to obtain information on the internal structure of opaque bodies.

The fluorescent screen method is used for many small objects where very small defects need not be detected. (Screening is much less sensitive than the photographic method.) The operator is completely shielded by lead from the rays and manipulates the specimen in the beam, using tongs and rubber gloves. Alternatively, heavier objects may be mounted in a thin spherical aluminium shell packed with cotton wool, which casts no appreciable shadow, the sphere being rotated in the beam mechanically for the examination of different parts. However, the photographic method is used almost exclusively for heavier castings, particularly where small defects are sought.

In practice, there are a number of complicating factors which must be considered in taking radiographs. These are :

(1) *Geometry*. The finite size of the focus of the X-ray tube tends to make fine detail in the radiograph blurred. The effect is analogous to the formation of umbra and penumbra in the shadow of a solid object, cast by an extended light source. The effect is reduced by placing the tube a long way from the specimen and the film as close as possible behind the specimen. Increasing the tube-specimen distance increases the exposure time (which is proportional to the square of the distance) and a compromise has to be made, depending on the amount of detail required.

(2) *Choice of Voltage*. An increase in voltage on the tube increases the penetrating power of the rays and consequently reduces the exposure time. On the other hand the contrast in the photographic image (and therefore the sensitivity) is decreased and again a compromise is necessary. For castings with a very wide range of thickness a relatively high voltage is sometimes used (if great sensitivity is not required) to reduce the contrast purposely so that the whole casting can be inspected on a single radiograph.

(3) *Scattered Radiation*. Part of the radiation absorbed by the specimen is scattered in all directions by the absorbing atoms and tends to obscure the radiograph by fogging. With objects of simple shape this is not important, but for more complicated ones, particularly at high voltages, special precautions have to be taken. Some of these are :

  (a) The use of absorbent blocking materials round the casting. Lead dust, lead shot and lead putty are commonly used. Suitably placed lead screens, to prevent scatter from one part of the specimen obscuring or producing spurious effects on another part of the radiograph, are also used.

  (b) Since the longer-wavelength (less penetrating) part of the X-ray spectrum is scattered to a greater extent, improvement is obtained by putting copper filters, which absorb the soft (long-wavelength) radiation preferentially, in front of the tube window.

  (c) Thin lead sheets placed in contact with the film, one on each side, have a double purpose. The one nearest the tube protects the film from the relatively soft scattered radiation and both act as intensifying screens since secondary electrons are emitted when they are irradiated and these affect the photographic film. The intensification factor is about 2 at 150 kV. but is less at lower voltages.

  (d) The Potter-Bucky grid. This consists of a series of parallel thin lead strips with their plane parallel to the X-ray beam and separated by wooden spacers. The grid is placed between the object and the film and is oscillated in a direction

parallel to the film during exposure. The main X-ray beam travels straight through the wooden spacers but the scattered radiation strikes the lead strips obliquely and is absorbed.

(4) *Intensifying screens.* Harder X-rays have less effect on the photographic emulsion, since they are less absorbed. Exposures can be very greatly reduced by using fluorescent intensifying screens in contact with the film. The screens, impregnated with calcium tungstate or zinc sulphide, fluoresce in the X-ray beam and the light affects the film.

The fact that a radiograph is simply a shadow picture means that images of the different layers are superposed. The location of defects can sometimes be obtained by taking two radiographs at different angles or it is possible to make a "planigraph" in which only the detail in one plane of the specimen appears. This involves moving tube and film during the exposure in such a way that the image of any point in a given plane of the specimen (parallel to the film) remains at the same point of the film, but the images of other planes move over the film and are therefore blurred.

Radiology is applied to the examination of the micro-structure of alloys by a special technique, known as microradiography. The specimen, of uniform thickness between 0.01 and 0.05 mm., is placed in contact with a special high-resolution film. A lead shield with a hole about 3 mm. diameter is placed over the top and a radiograph taken and enlarged. The distribution of the different elements present, if their absorption coefficients are sufficiently different, is indicated by the variation of intensity on the picture.

X-ray Diffraction

In a crystal the atoms are arranged in a regular three-dimensional pattern which can be considered as built up on a "space-lattice" of "lattice points" all similarly situated with respect to the pattern. If these points are joined by three sets of parallel lines, such that the three (one of each set) through any given point do not lie in a plane, then the pattern is divided into a number of exactly similar "unit cells" each being a parallelepiped containing a unit of pattern. The unit cell can of course be chosen in more than one way for a given set of lattice points.

Through the lattice points can be drawn sets of equidistant parallel planes, such that each set contains all the lattice points, and it can be shown that diffracted beams arise when the condition $n\lambda = 2d \sin \theta$ is satisfied, where λ is the wavelength, d the interplanar spacing for a set of these planes, θ the angle between the X-ray beam and the planes and n is an integer, the diffracted beam having the direction it would have if the incident beam were reflected by the set of planes. For this reason the diffracted beams are often spoken of as "reflections" although it is very important to remember

that, unlike light reflections from a mirror, a beam is only "reflected" from a set of planes (for a given wavelength) at one angle of incidence. It is clear that from measuring the positions of these diffracted beams it is possible to deduce the size and shape of the unit cell. The relative intensities of the reflections can be used to determine the positions of the atoms within the unit cell since the intensities depend on the form of the "unit of pattern".

The experimental methods of studying X-ray diffraction fall into two groups. In the first a single crystal is used, while in the second the specimen consists of a polycrystalline aggregate.

Single crystals are usually mounted in a narrow collimated X-ray beam containing a strong monochromatic line of known wavelength, and are rotated, or oscillated through a known angle, about an axis perpendicular to the X-ray beam during the exposure. Very small crystals, usually of linear dimension less than 0.05 mm., are used, and the diffracted beams are recorded as spots either on a flat film perpendicular to the X-ray beam or, more usually, on a cylindrical film coaxial with the axis of rotation. As the crystal rotates through the position satisfying the Bragg condition, $n\lambda = 2d \sin \theta$, for each set of lattice planes the reflection flashes out and is recorded on the film.

The geometry involved in interpreting the photographs is somewhat complicated, but graphical methods are used and the size and shape of the unit cell can usually be determined without much difficulty once the crystal has been set up with the correct orientation. This is fairly simple and can be done optically if the crystal has well defined faces, but in other cases it is necessary to take trial photographs from which the orientation can sometimes be determined. In this case the angle through which the crystal has to be turned is calculated and the adjustment made by means of the pair of graduated arcs at right angles on which the specimen holder is mounted. The final adjustment usually has to be made by trial and error.

There is a certain ambiguity in interpreting this type of photograph since there is no indication of the orientation of the specimen when a given reflection was produced. This is overcome in a number of different designs of moving film cameras. It is found that on a rotation photograph, as described above, the spots lie on a series of horizontal "layer lines" (see Fig. XV. 5), one of which is selected by means of screens, and the film is moved during the exposure. In the most common type, the Weissenberg, the film is cylindrical as described above, but it is moved parallel to the axis of rotation during the exposure, this movement being coupled to the rotation of the crystal so that the distance of a spot along the film in the direction of motion indicates the orientation of the crystal when that spot was reflected.

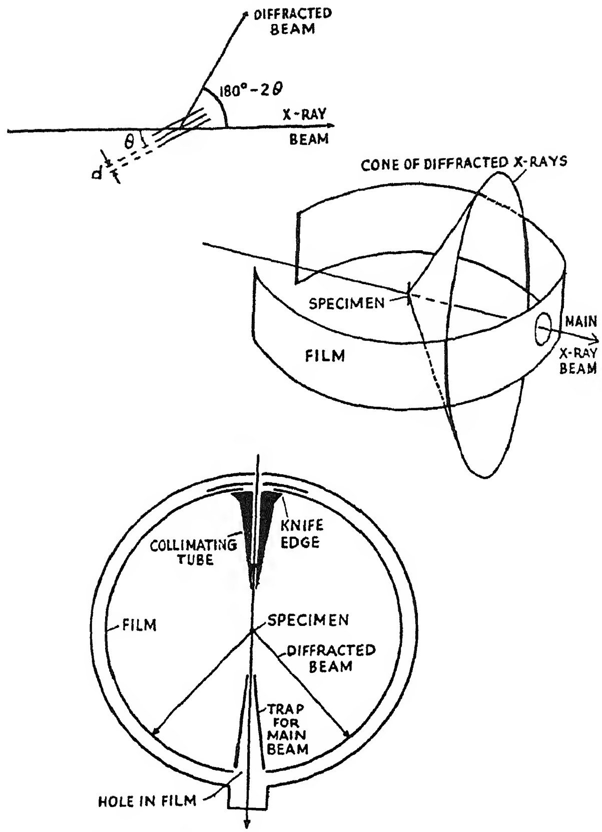


Fig. XV. 4. The principles of the "powder" method.

The geometry involved in photographs of polycrystalline aggregates (usually called "powders") is much simpler. The specimen consists of a very large number of tiny crystals, and for each set of lattice planes there will be some crystals with the correct orientation to reflect, so that all reflections are given at once. The diffracted beams are symmetrical about the incident beam and form a series of cones of semi-vertical angles (180°—2θ) with the incident beam as axis, these cones intersecting the film in a series of lines.

In the Debye-Scherrer type camera the specimen, in the form of a cylinder about 0.05 mm. diameter (either a powder mounted on a hair or enclosed in a thin cellophane tube, or a wire) is bathed in a beam of X-rays entering through a collimating tube. The film is a narrow strip bent into a cylinder about the specimen as axis. The main beam is trapped in an exit tube so that it will not fog

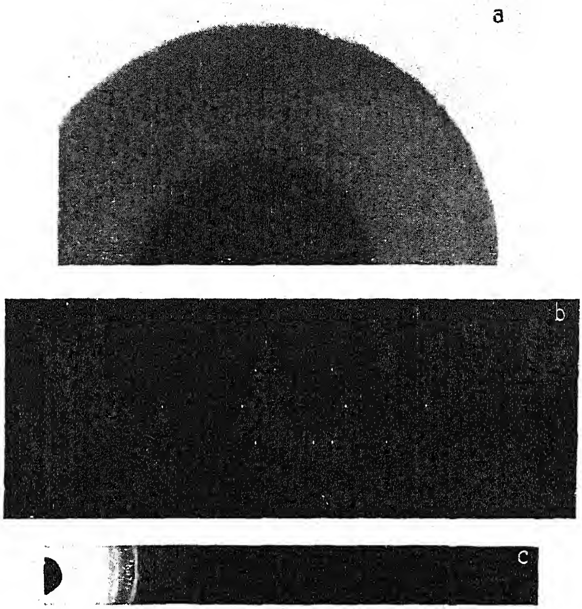


Fig. XV. 5. (a) Radiograph of light alloy casting showing porosity. (b) Rotation photograph of single crystal of quartz (Copper Kα radiation). (c) Powder photograph of quartz taken in 9 cm. diameter Debye-Scherrer camera (Cobalt Kα radiation).

the film. The specimen is usually rotated in the beam during the exposure (to increase the chance of each crystal being in a position to reflect) and is centred by adjusting it so that its shadow in the X-ray beam, viewed on a fluorescent screen, does not move from side to side when it is rotated.. Accurately ground knife edges, casting shadows at the ends of the exposed parts, act as fiduciary marks, so that the values of θ can be measured very accurately. The unit cell dimensions can be measured very accurately by this method, systematic errors being eliminated by using different lines on the film to estimate them and extrapolating to $\theta = 90°$. An accuracy of about 1 part in 20,000 is often claimed in accurate work. The intensities can also be measured more accurately than on single crystal photographs, but the disadvantage is that with crystals of low symmetry it is difficult to interpret the photograph unless approximate cell dimensions are already known. It is common in crystal structure analysis to use both single crystal and powder methods.

A few of the applications of X-ray diffraction apart from analysis of the atomic structure of crystals are :

(1) Identification of unknown phases. Since each crystalline substance gives its own characteristic diffraction pattern, the powder photograph can often be used in identification and analysis problems. This has been applied with great success to the study of phase diagrams, particularly of metal alloy systems. Equilibrium diagrams at high temperatures have been investigated in specially designed cameras containing a small furnace round the specimen.

(2) Particle size determination. If the "powder" is coarse the diffraction lines become spotty and this spottiness can be used to estimate crystal size. For crystals less than 10^{-5} cm. the diffraction lines are broadened and this effect can also be used.

(3) Internal stress in metals. Stresses in metals produce distortion of the crystal lattice which is shown by displacement and broadening of the lines.

(4) Preferred orientation of crystals in a solid specimen is detected by unevenness along the diffraction lines.

In all the types of diffraction photograph mentioned above it is the monochromatic radiation which is used. A range of wavelengths is obtained by using different target metals. The range commonly used goes from $\lambda = 0.56$ Å (Silver K_α) to $\lambda = 2.29$ Å (Chromium K_α). Usually the part of the "white" radiation which strikes the film is ignored—it produces a fogging of the film—but in some cases it is desirable to have as strictly monochromatic radiation as possible. The method employed is to reflect the beam from the X-ray tube by a monochromator crystal set so that a strongly reflecting set of planes is in position to reflect the characteristic line (but not, of course, the background). This reflected beam is then passed to the camera in the usual way. The exposure is increased many fold, but curved crystal monochromators have been developed which do not require more than double the exposure and give a focusing effect.

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CHAPTER XVI

ATOMIC AND NUCLEAR

What is the constitution of matter? The early Greeks, particularly Democritus, were the first to suggest the atomic structure of matter. Subsequent ideas were extremely confused until Dalton, on studying the laws of chemical change, postulated the ultimate division of elements into constituent atoms which, on combination with other atoms, produced molecules of the various compounds. An atom at this time was regarded as an extremely small ball of which the weight relative to one particular atom, namely the atom of oxygen, could be measured by chemical means, and the size of which could be ascertained approximately by physical means, such as observations on Brownian motion. During the last few decades, however, there have been a succession of discoveries which have led to the belief that the atom has a very complicated structure very similar to that of the solar system, although, of course, infinitesimally small. Among such discoveries are those of cathode rays (later called electrons) by Crookes, radio-activity by Becquerel, and perhaps most important of all, Rutherford's discovery of the nucleus, following his famous scattering experiments. The table given on p. 201 shows a list of the various atomic particles which have now been discovered and of which the role in atomic structure has been ascertained, although in some cases with uncertainty.

Briefly an atom consists of a nucleus containing protons and neutrons bound together by enormous forces, around which rotate electrons in specific orbits, the radii of which are much greater than the radius of the nucleus. To render the atom electrically neutral the number of protons in the nucleus is equal to the number of outer electrons.

The purpose of this chapter is to describe some of the more important instruments used to investigate atomic and nuclear phenomena. Those described are concerned mainly with the nucleus, since this is now the focus of attention. The most useful tool available for investigation of the outer electron structure is the spectrometer.

First of all there are the detecting instruments, and secondly the accelerating instruments with which particles may be accelerated to the extremely high energies necessary to overcome the large nuclear forces with the consequent production of interesting and valuable "nuclear transformations".

Detecting Instruments

Most detecting instruments depend for their action on the ability of charged particles to "ionise" gases through which they pass. During its passage through the gas, the particle will collide with many atoms of the gas, and at each collision it will probably knock out one or more of the outer electrons. The resulting particles will therefore be positively charged and are known as positive ions. In some gases, e.g. argon, the ejected electrons remain free, while in others, e.g. oxygen, they become attached to neutral atoms to form negative ions.

The Wilson Cloud Chamber

The Wilson Cloud Chamber is a device that renders visible the tracks of particles. It is well known that when a gas containing water vapour is suddenly expanded (adiabatically), the gas becomes supersaturated by the resultant cooling, and the water vapour will condense on any ions present, and these droplets of water can then be made visible and actually photographed. There have been several types of cloud chambers constructed, the earlier ones having the disadvantage that after the expansion various motions, such as eddying of the air, existed, which introduced distortion of the tracks.

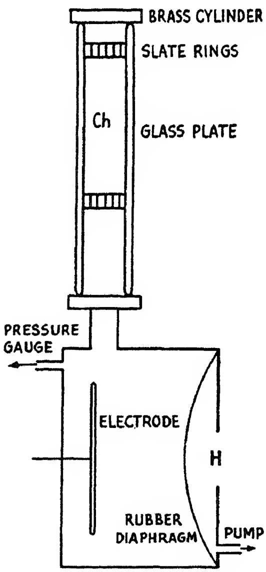

Fig. XVI. 1. The Radial Expansion Chamber. Ch is the Cloud Chamber formed by the annular slate rings separated by mica distance pieces and in which a sudden expansion is obtained by releasing a bung in the aperture H.

The radial expansion chamber, which removes this effect, and which is shown in Fig. XVI. 1, is in two parts, connected by a wide, short neck. The top portion, which is a brass cylinder closed at each end by circular glass plates, contains a cylindrical slit system consisting of a pile of slate rings held together by three glass pegs and separated by mica distance pieces. This portion constitutes the cloud chamber proper, the slit system rendering the expansion radial. The lower brass cylinder is closed at each end by brass plates, one of them, across which is stretched a rubber diaphragm, having a hole 3 cm. diameter closed with a rubber bung. Both cylinders, except the portion on the bung side of the diaphragm, are filled with the gas to be used, together with its quota of water vapour, at atmospheric pressure.

To effect an expansion the hole is closed with the bung and the gas in the cylinder is compressed to a suitable pressure by the

pumping of air into the space on the bung side of the diaphragm. The bung is then removed by the breaking of an electromagnet system which controls it, thus expanding the gas to atmospheric pressure. It is arranged to contain the tracks of the particles to be studied in the cloud chamber proper where the gas inside it expands radially through the cylindrical slit system. Such tracks are then photographed, usually by a system of two cameras, so that their final inspection can be made stereoscopically. Illumination is usually provided by quartz mercury vapour discharge lamps which are operated immediately after the expansion by a special timing mechanism. To prepare the chamber for the next expansion, the ions are removed from the top cylinder by an electric field applied between copper rings at each end of the pile of slate rings, while the electrode in the bottom cylinder removes stray ions in that region.

The Cloud Chamber is particularly useful for work with α and β-rays, and among the measurements usually carried out are the number of ions produced per unit length of track, the range of the particles, the momentum, energy and mass. The ionising effect of X-rays can also be studied, and it is now applied in the study of artificial disintegration and uranium fission. When the phenomena to be studied are of rare occurrence such as cosmic rays, it is found advantageous to use a completely automatic chamber. Before passing through the chamber the ionising particle passes through a Geiger-Muller Counter (see below) which automatically operates the expansion, the illumination and, finally, the exposure of the track.

The Ionisation Chamber

The Ionisation Chamber is a device for counting charged particles, and again uses the fact that such particles ionise gases through which they pass. If a source of high potential (D.C.) is applied across the gas, the positive and negative ions will be swept in opposite directions towards the electrodes, and the voltage pulse produced at one of the electrodes may then be amplified to operate a mechanical counter.

The chamber is usually designed to suit each particular job, but in general it takes the form shown in Fig. XVI. 2. The electrodes are contained in a metal cylinder into which the gas to be used can be introduced through the inlet tube. The electrode connected to the amplifier unit is called the "collector electrode", and is usually arranged to collect negative ions or electrons (depending on the gas used) by connecting the other electrode to a high negative potential. Since the voltage pulse

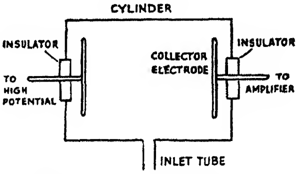

Fig. XVI. 2. The Ionisation Chamber. Electrons or negative ions formed in the chamber are collected by the "collector electrode" and the resulting voltage pulse is amplified to operate a mechanical counter.

obtained when even the most energetic particle passes through the gas is only a millivolt or less, an amplifier with a gain of about a million is required to produce pulses of sufficient magnitude to operate the mechanical counter.

The instrument can be used for counting highly ionising particles such as α-particles or protons. It cannot be used for β-particles since they produce insufficient ionisation, with the result that the corresponding pulse is not greater than the "noise" of the amplifier and will therefore not be recorded.

The Geiger Counter

This is an instrument very similar to the ionisation chamber but employs the additional principle that, if the electric field is sufficiently strong, the ions, produced by the passage of a particle through the tube, will produce further ionisation as they move towards the electrodes. This accumulative ionisation results in the production of a so-called "avalanche" of electrons which is swept very rapidly towards the positive electrode (in this case the collector), the formation of negative ions being unimportant. The electrical pulse obtained in this way depends upon the design of the tube, but is usually between 1/10th volt and 10 volts, hence it is only necessary to use a low gain amplifier, if any, to produce a pulse of sufficient magnitude to operate a mechanical counter.

The Geiger-Muller counter, shown in Fig. XVI. 3, consists of a glass (or metal) tube into which two electrodes are sealed, a straight piece of tungsten wire stretched down the middle (the collector) surrounded by the negative electrode which takes the form of a copper cylinder. With this arrangement the electric field around the wire is extremely intense. The tube is usually filled with argon at low pressure, but in this case the accumulative ionisation is so great that, unless the discharge is "quenched" by arranging the electrical circuit attached to reduce automatically the voltage across the tube, it becomes continuous. An alternative method of quenching is to mix the argon with alcohol vapour or methane.

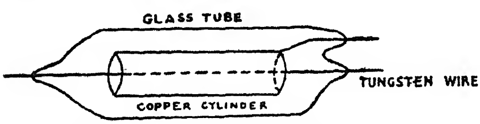

Fig. XVI. 3. The Geiger-Muller Counter. The "electron avalanche" produced by accumulative ionisation is collected on the central tungsten wire.

The Geiger-Muller tube is therefore an extremely sensitive device for detecting charged particles and is able to detect β-particles as well as the more highly ionising particles.

Accelerating Instruments

There are two types of accelerating instruments, those that produce a high voltage which is then applied to an electrode to

make the acceleration, and those that accelerate the particles directly without the production of the high voltage. The Cockroft-Walton and Van der Graaf generator belong to the first class, and the Cyclotron and Betatron are examples of the second.

The Cockroft-Walton High Voltage Generator

The action of the Cockroft-Walton Generator depends upon the fact that if each of N condensers is charged up to a certain potential E, the total potential developed across the N condensers in series will be NE. The charging is accomplished by the use of a very ingenious switching device with diodes acting the role of switches.

Fig. XVI. 4 shows a theoretical layout of a Cockroft-Walton Generator consisting of six condensers, six diodes and a transformer which we will assume delivers a peak voltage of E/2. When point A is positive with respect to B, diode D6 conducts, and condenser C6 is charged to a potential E/2 leaving the point C at a potential E. When A is negative with respect to B no current is passed, and so the potential of C oscillates between O and E. When point C is at a potential E, condenser C3 is charged with its top plate positive also to a potential E, through diode D5. Such a state of affairs enables the condensers C3 and C5 to become connected through diodes D4 and D6, and hence the charge will be shared between them. This sharing of charge will continue between C5 and C2, C2 and C4, C4 and C1 respectively, and meanwhile C3 receives additional charges from the transformer so that the first chain will be followed by more. The process will continue until equilibrium is reached when all the condensers are charged to a voltage E, and 3E has developed across C1, C2, and C3 in series. In practice the condensers and diodes are housed in towers about 12 feet high, and the resulting high voltage is applied to an accelerating tube housed in a similar tower. The particles to be accelerated, usually protons, are produced in a discharge tube at the top of the tower, and are

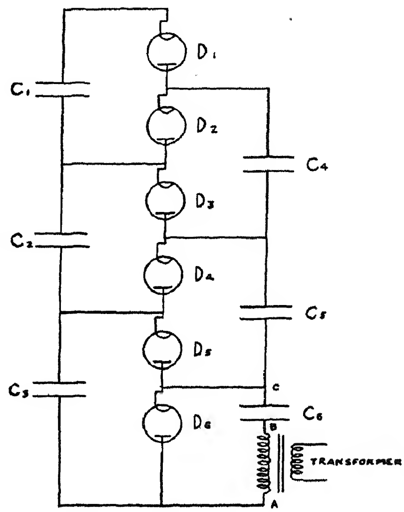

Fig. XVI. 4. Theoretical layout of the Cockroft-Walton Generator. C1—C6 Condensers. D1—D6 Diodes which act as automatic switches. The condensers C1, C2 and C3 are each charged to a potential E and the resulting potential 3E developed across them in series is used to accelerate particles in an accelerating tube.

allowed to pass down the tube where they are accelerated to high velocities in the intense electric field produced by the application of the high voltage to an electrode in the middle of the tube.

This machine has been used successfully to accelerate particles up to energies corresponding to 2 million volts, but like all high voltage generators it is limited by the insulation problems extremely difficult to solve in this case because of the size of the apparatus.

The Van der Graaf Electrostatic Generator

The Van der Graaf generator produces the high voltage electrostatically by continuously depositing charge on to a moving belt which passes through, and deposits its charge on to a large hollow sphere. The accumulation of charge on the latter results in its elevation to an extremely high potential which may then be applied to some form of accelerating tube.

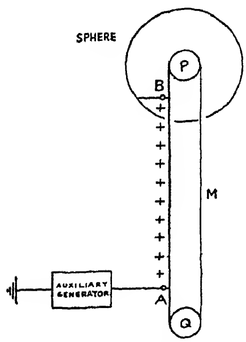

Fig. XVI. 5. The Van der Graaf Generator.
M. Moving belt.
P. Free pulley.
Q. Motor driven pulley.
A. Point which deposits charge from the auxiliary generator on to the belt.
B. Point which collects charge from the belt.
The sphere becomes charged to a high potential which can then be applied to an accelerating tube.

Fig. XVI. 5 shows a typical arrangement. Positive charge is sprayed on to the belt by the point connected to the positive terminal of an auxiliary generator. The silk belt, driven at high speed round the pulley fixed in the centre of the sphere by the motor-driven pulley, is designed to have a large surface area since the current output of the machine is equal to the rate at which charge is carried into the sphere. The charge is collected by a second point fixed in the sphere, and then transferred to the latter. The accelerating tube is usually fixed with one end inside the sphere.

Since this machine is more compact than the Cockroft-Walton machine, insulation difficulties can be more easily overcome by enclosing it completely (except for the output end of the accelerating tube) in a steel tank capable of being filled with air at high pressure. Dry air at high pressure has a greater resistance to electrical breakdown than "atmospheric" air and therefore enables the machine to be operated up to voltages of the order of 4 million volts.

The Cyclotron

The Cyclotron is an instrument which accelerates particles in steps, and consequently removes the insulation difficulties present in high voltage generators. It consists of two semicircular hollow

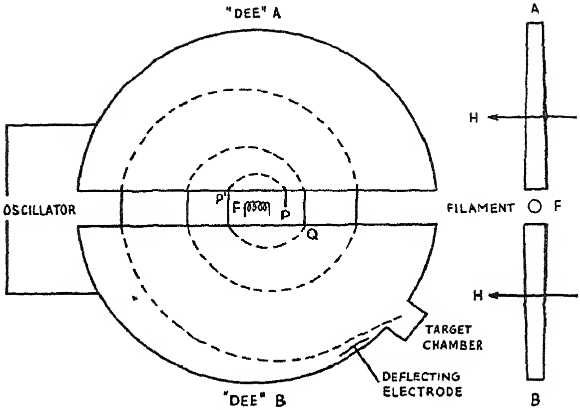

Fig. XVI. 6. The Cyclotron. Ions, generated near the filament F, travel in a spiral path under the influence of the magnetic field H, gaining an increment of energy at each crossing of the diametral region between the dees. At the end of their path the ions are deflected into the target chamber by the deflecting electrode.

plate electrodes, called "dees", across which high frequency electric oscillations are applied to produce an oscillating field in the diametral region between them, while a magnetic field is applied perpendicular to the plane of the dees. A positive ion at point P (Fig. XVI. 6), will be accelerated towards dee A if the latter is negative at this instant, and will then traverse a circular path inside the dee under the influence of the magnetic field. If the time taken for traversal of this semicircular path $(=\frac{\pi mc}{He}$ where m = mass of the ion, e = charge on the ion, c = velocity of light, H = magnetic field) is equal to the half period of the electric oscillations, the ion will receive another acceleration at point P′ into the now negative dee B. The ion will now travel in a circular path of larger radius owing to its increased velocity, but the time taken to reach point Q, where it will receive another acceleration, is again $\frac{\pi mc}{He}$. Hence it will circulate round in ever widening semicircles, gaining an increment of energy, corresponding to the potential difference between the dees, at each crossing of the diametral region until its radius is sufficient for it to be drawn away for examination. The mathematical formula expressing this condition for synchronisation is :

$$\frac{\pi mc}{He}=\frac{T}{2}=\frac{\lambda}{2c}$$

where λ = wavelength of electric oscillations.
T = period of electric oscillations.

It can be shown that if the amplitude of the electric oscillations is 4,000 volts and the ion makes 150 oscillations in all, its final energy will correspond to 1,200,000 volts.

A schematic diagram of the Cyclotron is shown in Fig. XVI. 6. The dees, made of copper sheet, are contained in a chamber filled with gas (usually hydrogen), the atoms of which are ionised by high speed electrons emitted from a filament mounted in the centre of the dees on a movable support enclosed in a watercooled copper shield. It is found desirable to design the filament to yield a large current at a low voltage to ensure the production of the optimum number of ions. After acceleration the ions are deflected by an electrostatic field applied to a deflecting electrode into the target chamber. The whole chamber is inserted between the poles of a powerful electromagnet designed to give a more or less uniform field perpendicular to the whole area of the dees. Lack of uniformity can afterwards be corrected by insertion of thin sheets of iron, called shims, between the poles and the dees.

What are the limitations of this type of Cyclotron? If the size is increased the instrument will be capable of producing faster particles, but a limit will ultimately be reached when the relativistic variation of mass takes effect at velocities approaching that of light, for the condition for synchronisation will be lost. This limit is reached at energies corresponding to about 10,000,000 volts.

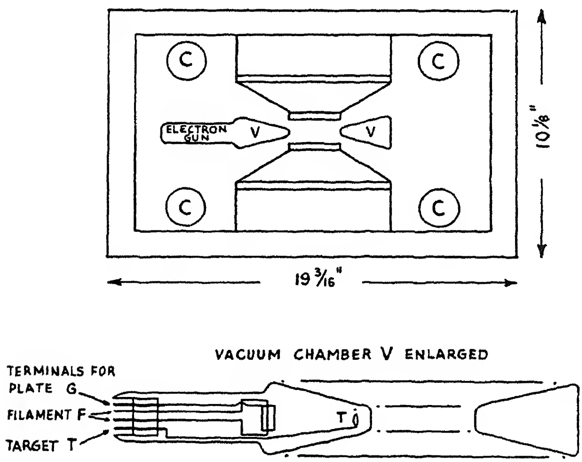

Fig. XVI. 7. The Kerst Betatron. Electrons, emitted by the filament F and focused by the plate G into the vacuum chamber V, are accelerated in the latter by the induction produced by the changing magnetic field and finally spiral inwards on to the target T. The magnet is excited by the coils C.

The Betatron

The Betatron depends for its action on the fact that an electromotive force is induced in a circuit when the magnetic flux through that circuit is varied. In the case of the Betatron the circuit is simply a circular stream of electrons in a tube, which are therefore continuously accelerated in their million or so circular trips as the magnetic flux is rapidly increased. Moreover it can be shown that if the velocity of the electrons and the magnetic field increase proportionately, the radius of the orbit will remain unchanged.

In Fig. XVI. 7, which is a diagram of the Kerst Betatron, the magnet, built of silicon steel laminations, is excited by two coils, each consisting of ten turns of highly stranded copper wire and tuned to resonance at a frequency of 600 cycles per second. The acceleration takes place in a vacuum chamber, constructed in one piece and coated internally with a thin layer of silver to prevent the accumulation of stray charges, which would otherwise affect the stability of the orbit. Injection of the electrons into the chamber is accomplished by an electron gun, where they are initially produced by thermionic emission

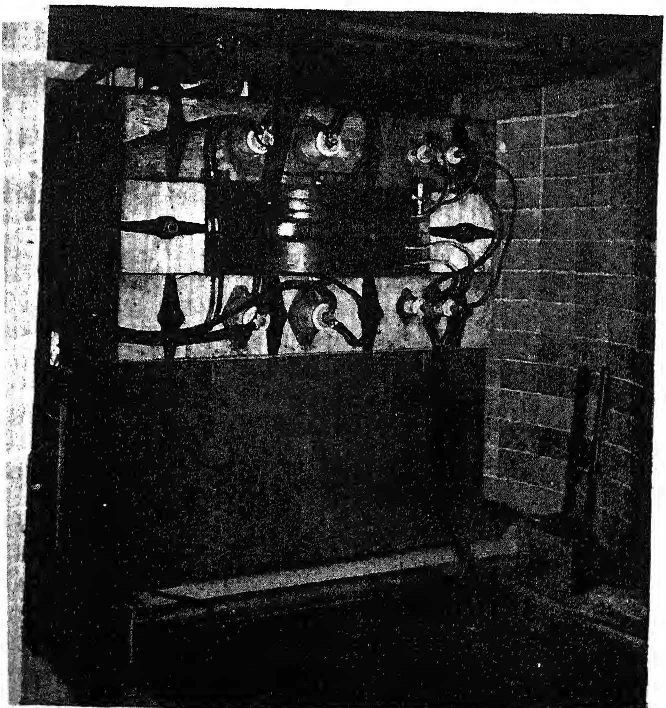

Fig. XVI. 8. A 20,000,000 volt Betatron built by Metropolitan-Vickers Electrical Company Limited.

from a tungsten filament and subsequently focused by a negatively charged plate. As the magnetic field passes through zero a burst of electrons is injected into the chamber and these are then accelerated in their stable orbit by the increasing field until the maximum field strength is obtained. At the end of the cycle the electrons are made to spiral inwards towards the target by the introduction of a small amount of iron dust into the magnetic circuit which saturates before the core, thereby forcing the velocity of the electrons to increase less rapidly than does the magnetic field.

The Betatron is capable of producing much higher velocities than the Cyclotron described because there is no phase synchronisation associated with it, and therefore relativity effects are eliminated. The Kerst Betatron is capable of producing 100 million volt electrons. Moreover, it is much smaller than the Cyclotron as can be seen by comparing the dimensions given in Fig. XVI. 7 with a Cyclotron having pole pieces 60 in. in diameter, at present in operation. It may be mentioned, however, that modern developments have led to the possibility of overcoming relativity effects in the Cyclotron, and also the production of even higher energies with another device called the Synchrotron. Fig. XVI. 8 shows a photograph of a 20,000,000 volt Betatron built by Metropolitan-Vickers Electrical Co. Ltd.

To illustrate the need for the high energies produced by these machines it is necessary to consider a law postulated by Einstein, namely, The Law of Equivalence of Mass (m) and Energy (E) which can be expressed by the formula $E=mc^2$ where c is equal to the velocity of light. It is found that the mass of a stable nucleus is less than the sum of the masses of its constituent particles. For example the mass of a deuteron is 2.0147 mass units (referred to Oxygen as 16 mass units), and the sum of the masses of a neutron and proton is 2.0171 mass units. Consequently there is a mass defect, as it is called, of .0024 mass units, which, according to the above law, is equivalent to an energy called the Binding Energy, of 2.2 million volts. This is the minimum energy which is required to split the deuteron into a proton and neutron. It is possible to apply such reasoning to all nuclei and to calculate the energies which must be applied to the bombarding particles to bring about the various nuclear reactions.

With such accelerating instruments the scientist hopes to overcome the forces which bind together even the most firmly bound nucleus. With the detecting instruments he can attempt to find out what has happened when the disruption occurs. The possibilities are immense. Besides the future industrial and medical applications the present somewhat hazy idea of the nucleus will be replaced by a closer approach to the reality of the structure of matter.

The table on p. 201 gives a summary of the properties of the fundamental particles of the universe. Except for the neutrino (a

ATOMIC PARTICLES AND THEIR PROPERTIES

PARTICLE	MASS	CHARGE	REMARKS
Electron	9.0×10^{-28} gm.	-4.77×10^{-10} e.s. units	Rotate in specific orbits around the nucleus, the orbit structure determines the spectrum of element.
Positron	9.0×10^{-28} gm.	$+4.77 \times 10^{-10}$ e.s. units	Positive equivalent of the electron existing in cosmic rays—have no permanent existence in matter of ordinary density.
Proton	1.67×10^{-24} gm.	$+4.77 \times 10^{-10}$ e.s. units	A positively charged nuclear particle—atom has same number of protons in nucleus as electrons in outer structure to make it electrically neutral.
Neutron	1.67×10^{-24} gm.	0	Electrically neutral nuclear particle.
Neutrino	$<10^{-29}$ gm.	0	Hypothetical particle introduced to explain the erroneous results concerning energy and spin when accounting for emission of electrons by radio-active elements—it is assumed that a neutron disintegrates into a proton, electron and a neutrino.
Meson	Approx. $200 \times$ mass of electron	$\pm 4.77 \times 10^{-10}$ e.s. units	Occur in cosmic rays.
α-Particle	6.68×10^{-24} gm.	$+9.54 \times 10^{-10}$ e.s. units	Particle, consisting of two neutrons and two protons, emitted by radio-active substances with velocity depending on the substance.
β-Particle	9.0×10^{-28} gm.	-4.77×10^{-10} e.s. units	Electrons emitted by radio-active substances with velocities approaching that of light.
Deuteron	3.34×10^{-24} gm.	-4.77×10^{-10} e.s. units	Particle consisting of one proton and one neutron—nucleus of heavy hydrogen atom.
γ-Rays	0	0	An electromagnetic wave of very short wavelength emitted by radio-active nuclei.
X-Rays	0	0	Similar to γ-rays but have slightly longer wavelengths and are associated with atomic (outer electron structure) rather than nuclear processes.

particle whose mass is believed to be less than a hundredth the mass of an electron, and without any charge) which has been introduced to explain β-radio-active disintegration, and which has not been detected experimentally, and some properties of mesons, the particles and their properties are firmly established. It must be borne in mind, however, that although these particles and their masses and charges can be tabulated, little is known of their real nature. In the present state of knowledge they are best described in terms of abstract mathematical symbols ; ordinary language has been found to be inadequate.

Nevertheless most of our knowledge on which these deductions are based is obtained directly through the use of instruments, most of them obviously of a highly specialised character which it is felt puts them beyond the scope of such a book as this. Such instruments may, however, be regarded in the majority of instances as specific elaborations of the more general type herein described.

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SECTION 5

MATERIAL TESTING INSTRUMENTS

CHAPTER XVII

METALS

The testing of materials has become very important in engineering, since their proper use is dependent upon the accurate knowledge of their properties, which can only be determined by means of tests. The rapid development of the application of physical methods to the examination of metals has become very specialised, with the result that although different methods may sometimes overlap, they are, generally speaking, complementary, not only to each other, but to the more generally used methods.

The British Standards Institution have formulated and published standards and methods of tests for materials. Some organisations have their own special tests for the materials they use. In every systematic test, some type of testing machine or instrument is used to evaluate the properties of the material.

The primary tests usually carried out are : tension, compression, transverse bending, shearing, and torsion. In addition to these primary tests there are various special tests, such as hardness, impact, fatigue, temperature creep and magnetic properties, etc. In general, special purpose instruments and machines are required for each type of test except tension, compression and bending, for which the Universal testing machine is used, which can be of the single lever, compound lever or hydraulic type.

Universal Testing Machines

Fig. XVII. 1 illustrates a Universal testing machine of the vertical single lever type which can be used to make tests in tension, compression, bending, shearing, torsion and hardness on any metal. For shearing, torsion and hardness tests, separate attachments are used.

In any test the load is applied to the test piece by the downward movement of the straining crosshead, which is operated by means of an electric motor driving through spur and worm gearing. A hand wheel can replace the motor and the load is transmitted to the weighing steelyard, where it is balanced by a travelling weight or poise and indicated on a graduated scale.

If a tensile test is to be done, the specimen is placed between the weighing crosshead and the straining crosshead. Special types of grips are used for different specimens, those for wire rope and small chains being different from the usual wedge type grip used for ordinary tensile tests. There are also special grips for holding screwed or headed specimens.

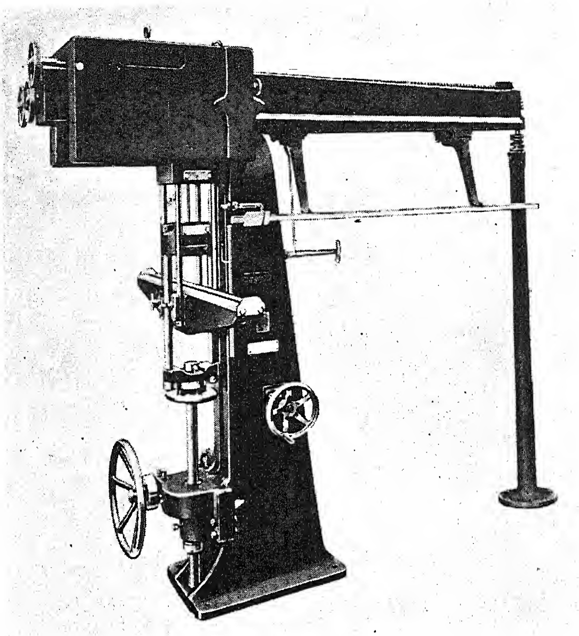

Fig. XVII. 1. Universal testing machine, vertical single lever type.

For a compression test, the specimen is placed on the beam directly under the straining crosshead. This beam is suspended by four steel rods from the weighing crosshead. The load on the test piece, caused by the downward movement of the straining crosshead, is thus transmitted direct to the steelyard. If extremely accurate results are required, it is usual to use a self-aligning, spherically-seated compression block to prevent eccentric loading of the test piece. For a transverse bending test, the specimen is supported on the beam and the load is applied to the middle of the beam by the straining crosshead. This machine can also be used to test semi-elliptic springs or quarter-elliptic springs.

When a shearing test is to be made, a special attachment is used to hold the specimen. This attachment is accommodated between the compression platens and the test is carried out under compression conditions.

For a torsion test a different special attachment is used, which is bolted to the column of the machine. The specimen is held at one end in a holder which is attached to a shaft rotated by the hand wheel through spur and worm gearing. At the other end, the specimen is secured to a holder which is mounted in ball bearings

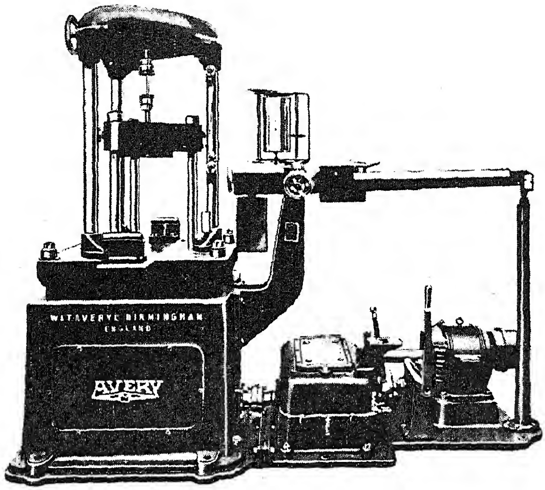

Fig. XVII. 2. Universal testing machine, compound lever type.

and is attached to an arm, the end of which is connected to a subsidiary knife-edge on the steelyard. The pull on the end of this arm, to the movement of the poise weight on the steelyard, provides the necessary resistance to the torque applied to the specimen and this is recorded in inch-pounds on the second steelyard scale. This machine is made in various capacities from 10 to 100 tons.

Fig. XVII. 2 illustrates a Universal testing machine of the vertical compound lever type. These range in capacity from 10 to 500 tons, and differ from the one just described, in that the construction is similar to that of the orthodox platform weighing machine. The upper tension crosshead is supported on steel columns secured to the compression table. The straining crosshead is secured to steel screws which engage with rotating nuts in the base box of the machine, and the nuts are rotated by means of worm gearing and an electric motor. A friction clutch is provided between the motor and the gear-box so that the speed of the crosshead can be controlled.

The same tests can be carried out on this machine as those already described, with the exception of the torsion tests. In addition, with special attachments, tests on railway couplings and hooks, as well as on porcelain insulators, are possible.

Another type of testing machine is the self-indicating, hydraulic Universal testing machine. This machine is illustrated in Fig. XVII. 3, and differs considerably from those already described, in that the straining unit is a single vertical cylinder and hydraulic ram for applying the load, together with grip holders and platens

for tension and compression tests. The moving grip holder and transverse beam are suspended from the ram head by means of twin tension rods. A ball seating on top of the ram ensures correct alignment. The beam grip holder is mounted on the end of a

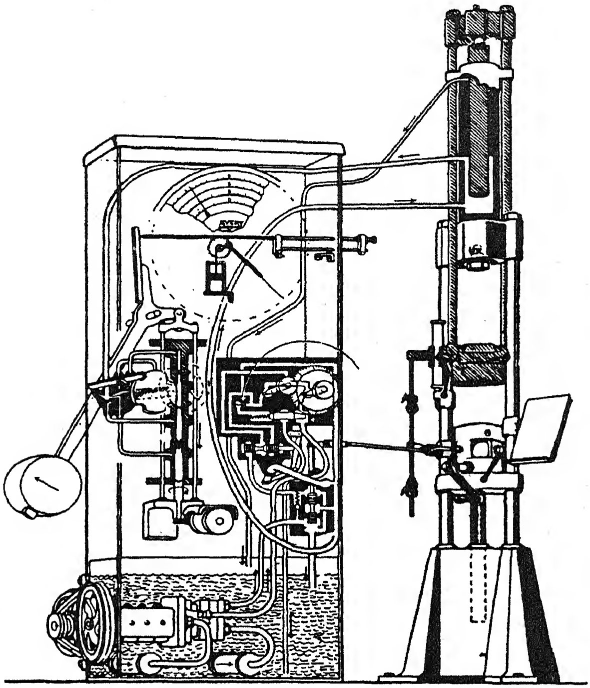

Fig. XVII. 3. Diagrammatic view, showing general arrangement of self-indicating universal testing machine.

substantial adjusting screw which fits into a nut in the base. Adjustment is through bevel gearing to a screw, the holder being guided by means of a bracket running on the main support rods. An adjustable extension scale is carried from one of the rods and a vernier is fixed to the moving grip holder. The indicating mechanism is housed in a cabinet, together with the valve controls, the pump, and a pendulum resistant unit, the pendulum itself being mounted at the back of the cabinet.

The quadruple proportional cylinder is provided with four rams, each of different diameter to suit the chart capacity required, and the appropriate ram is selected by means of a four-way valve, operated by the capacity change hand wheel. To reduce friction to a minimum, the proportional rams are kept in continuous rotation by a small

electric motor. There are four scales : full, half, one-fifth and one-tenth capacity. This machine can be used for tensile, compression and transverse bending tests. Shearing and hardness tests can also be carried out on the machine with the addition of special equipment. The machines are made in 10, 30 and 50 ton capacity.

All the machines described above are suitable for the testing of large specimens, and the minimum length of specimen that any of them can accommodate for a tensile test is two inches. In some cases it is impossible to obtain specimens of this size from the material to be tested, for example, it may be necessary to test a connecting rod of a petrol engine that has broken in service, to find out whether the material was defective, or whether there was insufficient material used.

Hounsfield Tensometer

A machine capable of testing small specimens was designed by L. H. Hounsfield and is called the Hounsfield Tensometer. It is a universal tensile testing machine capable of pulling test pieces turned from bar material, wires, sheet metal, plastics, textiles and films. It provides for such tests as notched bar, shear, compression, Brinell and other indentor tests, 180° bend test and cupping. It also has the advantage of having an autographic recorder which can be used even for an indentor test. It can also be adapted with the aid of a small furnace for testing materials up to 1,000° C. Materials for the Rolls Royce jet engine were tested on this machine. Since it is possible to cut test pieces from bars in three directions at right angles, as well as from the centre or surface as may be required, a complete picture can be obtained of the material under test, which cannot be obtained with the larger test pieces. The contention that these small test pieces do not give average results, is true only to a very limited extent. The usual 0.564 inch diameter test piece is only about three times the diameter of the usual 0.178 inch diameter Tensometer test piece, and the effect of small errors is proportional to the diameter and not to the square of the diameter as is so often supposed. These test pieces need not be made very accurately, as a correction table for errors is provided.

The machine itself is illustrated very diagrammatically in Fig. XVII. 4, which shows the essential features shorn of all details. The load is applied at one end, its magnitude being measured at the other, and the application is usually by a handle, but a motor drive can be fitted. The load is taken through the tension head to the spring beam, the ends of which are supported on rollers and its deflection is transmitted through a vertical lever to a mercury piston, which displaces mercury in a glass tube. Movement of the mercury is followed by a cursor and the needle is made to puncture the graph paper at frequent intervals, thus recording "force" vertically. The

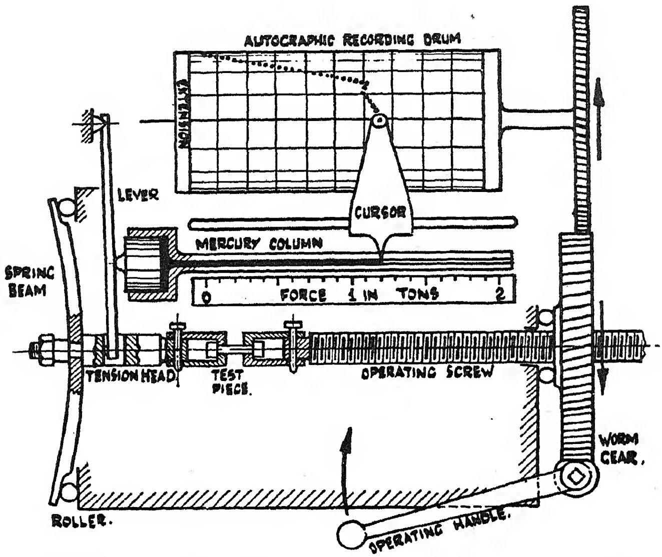

Fig. XVII. 4. Diagrammatic view of Hounsfield testing machine, showing essential features.

movement of the worm gear is transmitted to the spindle of the recording drum through gears and this enables "elongation" to be recorded horizontally.

The machine has seven interchangeable spring beams capable of taking maximum loads of from 62½ lb. to 2 tons. The graduated force scale is also interchangeable and a special scale is provided with each spring beam. Beams and scales calibrated in kilograms can be supplied.

Compression and shear tests can be carried out on the machine by means of a special compression attachment. Other tests, such as hardness, etc., can also be carried out on this machine.

Large Horizontal Testing Machines

When tests on built-up structural members are required, none of the machines already described is of much use. In fact, nothing under about 300 tons capacity can be used. The best examples of large machines built in this country are: the 300 ton Avery Machine at Birmingham University, and the 1,250 ton Universal Testing Machine built by Avery Ltd., for Messrs. Dorman, Long and Co. Ltd. Fig. XVII. 5 illustrates this machine, which is claimed to be the world's largest universal testing machine. One of its first duties was to carry out experimental work in connection with the Sydney Harbour Bridge. The machine is of such large proportions

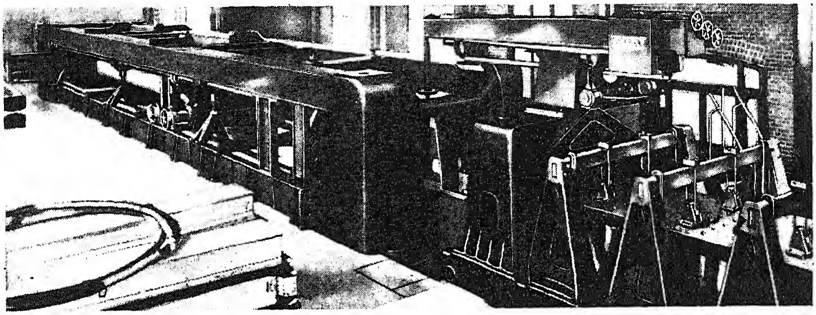

Fig. XVII. 5. Avery 1,250 ton universal testing machine.

that built-up compression members, 50 ft. long and having a cross-section of 45 sq. in., can be tested to destruction ; and in tension, round bars up to 6 inch diameter and flat specimens 12 inches wide and 3 inches thick, up to 50 ft. long. For transverse tests, complete lattice girders, 42 inches wide and 50 ft. long, can be tested. From the above brief description it must not be inferred that this machine only gives approximate results, for in it Messrs. Avery use their well-known principle of recording the applied load entirely through the medium of weighing levers, so that readings from zero to 1,250 tons by 1/10th ton can be obtained.

Calibration of Testing Machines

Every machine is, of course, calibrated by the makers. The most satisfactory method is to use dead loads through the full range of the machine. Where dead weight loading is not practicable, proving levers are perhaps the best.

Another method is by means of a standard weight-bar—a bar whose modulus of elasticity is known by previous experiment.

Extensometers

In carrying out tensile or compression tests it is often necessary to measure minute extensions or compressions of the specimen for stresses up to the elastic limit. The instruments used for this purpose are called extensometers or compressometers. They magnify the stretch or compression of the specimen, either by optical or mechanical means, and measure it to a high degree of accuracy.

The "Cambridge Extensometer" is an instrument of the mechanical magnification type, and it was capable of measuring down to 1/1000th of a millimetre. The instrument was first patented in 1908 but is now out of production ; it was a very robust instrument but is now replaced by the Ewing type of extensometer.

Ewing Extensometer

This instrument was designed by Sir J. A. Ewing, F.R.S. It is an example of optical magnification and with it the stretching of the specimen can be watched continuously. It can be used on large or small specimens and its principle of operation is shown diagrammatically in Fig. XVII. 6. It is clamped to the specimen by two pairs of set screws with steel points, the distance apart of which is accurately adjusted, so that a definite length of the specimen is under observation. The upright rod, projecting from the lower clamp, ends in a rounded point which engages with a conical hole in the upper clamp, thus forming a fulcrum about which the clamp rotates when an extension of the specimen takes place. A point equally distant from the rounded point on the opposite side of the top clamp, moves relative to a point on the lower clamp through a distance equal to twice the extension of the specimen. This movement is measured by means of a microscope fixed in line with the lower clamp and focused upon a fine cross wire on a rod pivoted as shown on the right-hand side of the figure. This cross wire is illuminated by means of a small mirror, and the displacement is read on a micrometer scale in the microscope eyepiece graduated 0—140 divisions, each of which, in the 2 inch and 8 inch instrument, represents an extension of 0.0002 inch in the specimen. Readings can be estimated to 0.00002 inch. This instrument is used a great deal for scientific work in this country.

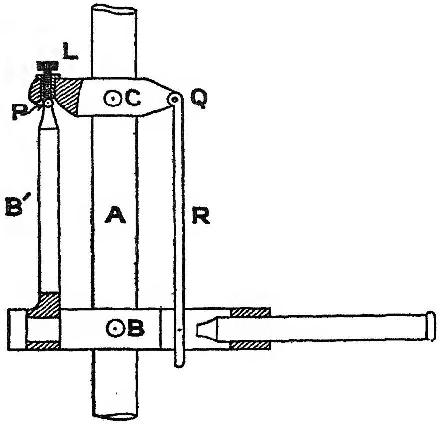

Fig. XVII. 6. Diagrammatic view of the principle of the Ewing Extensometer. A is the test piece. B and C, the clamping pieces. B^1, the projecting rod from lower clamp B. L the micrometer screw, the end of which forms a conical socket. P, the rounded point of the rod B^1 which engages in the conical socket in the upper clamp C, which is the fulcrum. Q the point on clamp C which moves relatively to B. R a rod pivoted at Q which carries the cross-wires.

A modified form of this extensometer can be used for measuring the elastic compression of short blocks.

The Lindley Extensometer

This instrument, which is illustrated in Fig. XVII. 7, is a robust, simple and practical instrument which is capable of accurately measuring extensions to $\pm$ 0.00005 inch, this can be obtained with a gauge length of 2 in. In fact, the degree of accuracy to which

the extension is measured is greater than the accuracy with which the load applied or the area of the specimen can be gauged. The principle of the instrument is simple. The extension of the material under test is magnified in the ratio of 2 to 1 by a single lever, and

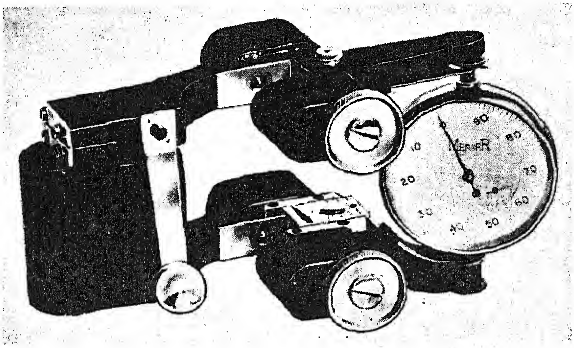

Fig. XVII. 7. The "Lindley" extensometer gauge, length 2 in. Magnification factor 1250 : 1.

thereafter measured and indicated by a "Mercer" dial gauge graduated in ten thousandths of an inch. One division on the gauge indicates an alteration in length of the specimen of 0.0005 inch. A further interesting point is that the instrument is always in static balance about the axis of the specimen, so no errors due to the weight of the instrument bending the specimen are introduced; also errors due to gripping do not affect the dial reading. If this instrument is used on very small cross section specimens, the weight of the instrument should be taken into consideration.

Another extensometer of the optical type is the Lamb designed by Professor E. H. Lamb and described in *Scientific Instruments*, page 120.

Compressometers

Most of the extensometers already described can also be used as compressometers provided that the specimen is of sufficient length to take them. It is, however, often necessary to modify the method of attachment.

Strain Gauges

These are special forms of extensometers used to measure changes in length on the surface of various portions of a structure. The strain gauge is used for determining the actual distribution of the deformations at the extreme fibres of a member and is the principal instrument used in "field tests," but it is also used in the laboratory. (See also Chapter XII, page 152.)

Torsion Testing Machines

For testing the shearing strength of a material the torsion test is the most suitable, since the test produces pure shearing stress in a round specimen. Many of the machines already described have attachments fitted so that a torsion test can be carried out, but it is usually more convenient to have a separate machine for the test. Fig. XVII. 8 illustrates such a machine. The specimen, which is

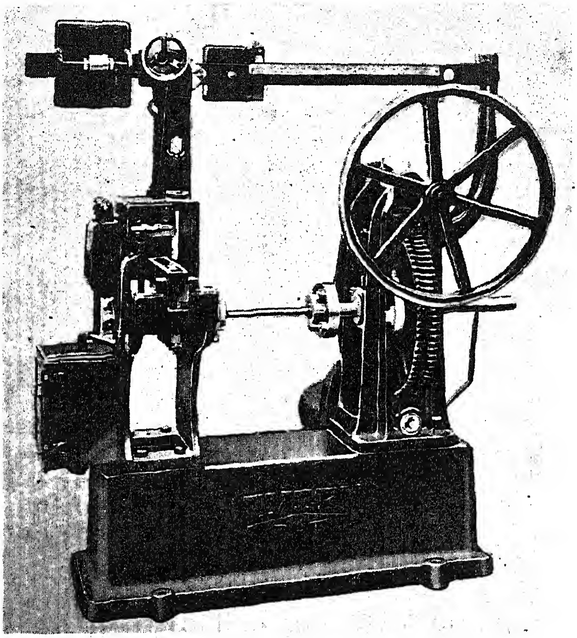

Fig. XVII. 8. Torsion testing machine.

prepared at each end with keyways, is held by a chuck at each end. One chuck is rigidly attached to worm-wheel gearing with which is a worm whose spindle carries a hand wheel or a motor drive. The other chuck is connected through a lever and linked to a graduated arm carrying a counterpoise. On rotation of the hand wheel, the other end tries to rotate and exerts a pull on the graduated arm so that the counterpoise is moved until the arm floats in a horizontal position. The angle of torsion is indicated upon a graduated scale of degrees and the machine can also be fitted with an autographic recorder.

When the coefficient of rigidity is required, accurate observations are necessary, so all instruments used for this purpose must be independently fixed on the bar, with a definite gauge length. If a

very high degree of accuracy is not required, two long pointers clamped on the specimen at a given distance apart which move over a fixed scale will suffice, and the difference between the readings is a measure of the torsional strain.

Torsional Strain Indicators

These instruments are used when a high degree of accuracy is required in determining the coefficient of rigidity. Space does not permit the description of the many types of indicators, but in the Coker Torquemeter the gauge length is 8 inches and at one end of the specimen is fixed a graduated circular plate on which an arm and vernier are attached which can be moved round it, and to which is attached a frame which carries a cross wire and a mirror. On the other gauge mark is fixed a chuck which supports an arm, having attached to it a micrometer microscope which is sighted on the vernier plate frame. As the torque is applied, the cross wire moves relative to the microscope. The movement can be measured to about one second of arc.

Lamb's Mirror Torsion Meter

This is a very accurate instrument for measuring small torsional strains. It is placed over the specimen and is clamped by screws, held in universal joints, a method that eliminates bending strains. Two mirrors are provided which are adjustable. A telescope with cross wire and two scales are required to observe the relative angular movement of the mirrors.

Fatigue Machines

Static tests must be supplemented by other tests resembling closely the conditions under which the material is used, since materials fail under stresses much lower than the ultimate when the stresses are repeated many times. The machines used to test this property are called Fatigue Machines, and may be classified under four main types: (a) Rotating Cantilever Machines, (b) Rotating Bar Machines with a short length of the material under a constant bending moment, (c) Direct Stress Machines in which the load is applied by a rotating mass which is unbalanced, (d) Direct Stress Machines in which the load is applied by an electromagnet excited by an alternating current.

In the Rotating Cantilever type of machine, Fig. XVII. 9 (left), the specimen is held in a rotating chuck which is driven either directly or through gearing. The specimen is loaded at the other end by a weight which is attached to the specimen by a ball bearing. The number of alterations is recorded by a counter. The machine is automatically switched off when the specimen breaks.

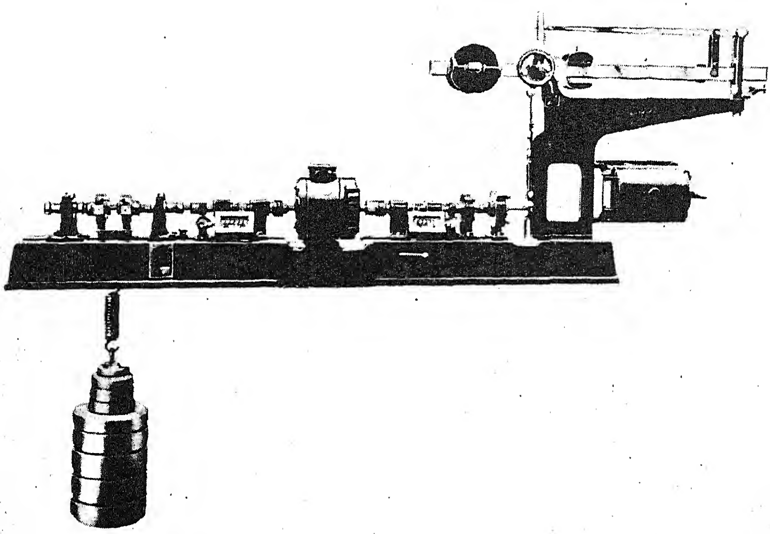

Fig. XVII. 9. Combined fatigue testing machine which incorporates two types of machines on one bed. On the left the cantilever and on the right the beam.

The Rotating Bar machine, illustrated in Fig. XVII. 9 (right), was introduced by Sondericker. The specimen is held at each end, i.e. as a beam, and two equal loads are applied at points equidistant from the supports. This is known as four point loading. The portion of the specimen between the loads is thus subjected to a uniform bending moment, while revolving on its axis.

In carrying out fatigue tests on the machines described, not less than four specimens are tested. The first one is considerably overstressed and the number of reversals before failure noted. The second specimen is not so highly stressed so the specimen will withstand a greater number of reversals before failure. Further specimens are tested until a loading is found so that the specimen will withstand a predetermined number of reversals. Endurance tests up to five million reversals are sometimes used.

Direct Stress Machines

In this type of machine the load is applied by an unbalanced weight. Unfortunately, the machine suffers from the disadvantage that the inertia forces vary with the square of the speed, so it is necessary to control the speed very carefully in order to obtain reliable results.

The Haigh repeated stress machine is a good example of this

last type. The electro magnet is excited by an alternating current from a generator giving a sine wave e.m.f., so that the pull is almost proportional to $\left(\frac{\text{Voltage}}{\text{Frequency}}\right)^2$ and is nearly independent of the air gap, which is small. The pull pulsates with twice the frequency of the current.

Impact and Notched Bar Testing

The tensile test does not give all the information that the designer requires to know. For example, parts of machinery sometimes fail when subjected to shock. In consequence, various methods have been devised to give accurate information of the shock resisting properties of materials.

A considerable amount of work has been carried out in England on the notched bar test and in consequence two forms of impact test-pieces have been standardised which can be broken either as a beam or as a cantilever. The principal type of such machines is the Izod, which has a capacity of 120 ft.-lb. The specimen is 10×10 mm. and is notched with a 45° V notch 2 mm. deep with a root radius of 0.25 mm., and is securely clamped in an anvil fixed to the base of the machine. The pendulum is held in its raised position by means of a spring-loaded trigger. On release, the pendulum falls and expends some of its energy in fracturing the specimen. The residual energy in the pendulum causes it to continue its swing and, in doing so, it carries forward a pointer which indicates on a graduated chart the amount of energy absorbed by the specimen.

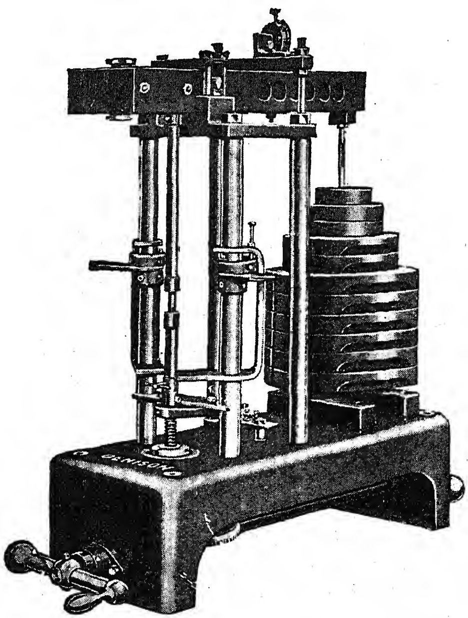

Fig. XVII. 10. Creep testing machine. (Furnace not shown.)

Creep Testing Machines

The mechanical properties of metals are severely modified by rise in temperature. For example, the tensile strength of mild steel increases with temperature up to about 300° C. and then falls. At 500° C. it is only about 50 per cent of that at atmospheric temperature. The elastic limit falls as the temperature rises, while the elongation diminishes up to about 200° C.

and then increases. Other metals exhibit widely different temperature characteristics. Owing to the increasing use of steel and other metals at high temperatures, various machines have been developed to measure these characteristics.

The general principle of the machines is to apply the load at a given rate of strain which can be altered to suit the particular specimen. The load and extension are usually recorded automatically, but can also be measured directly. The temperature of the specimen is kept constant to very fine limits. Fig. XVII. 10 illustrates one type of these machines made by Samuel Denison & Son Ltd. It has a capacity of 5 tons and is based on a design by the National Physical Laboratory. The machine is intended for use with a modified Martin's type mirror extensometer. The straining and weighing gear are of usual design and the furnace is suitable for temperatures up to 900° C. There are, of course, many other types of creep machines.

Hardness testing machines have already been described in Chapter XXVIII of *Scientific Instruments*, and the reader is referred to this chapter for information. Space does not permit of a description of machines used for testing building materials except to say that they are similar in principle to those already described.

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CHAPTER XVIII

FABRICS

When a cloth or, in fact, any textile material is required to be "tested", its strength is the feature perhaps most often in mind. Naturally, there are many other physical properties of the interlaced system of threads, which we call a fabric, that can be measured or described. Most of them need machines, instruments or special apparatus for the purpose. Weight, thickness, permeability, stiffness, resistance to abrasion, electrical or thermal characteristics and so on, are notable examples. Others involve structural details which can be probed by dissection, observation under magnification and counting. In the first group are strength with extensibility and, in a lesser degree, elasticity as a concomitant.

It is usually accepted that the act of determining the strength of the material not only records the resistance to actual rupture by measuring the load necessary to strain it to breaking point, but gives an idea of the probable performance in use, including the possible length of service. Clearly also, faults in structure or chemical weakness will be inclined to show themselves if enough strength tests are carried out.

Although, in the main, fabrics often seem unsubstantial, they need heavy instruments to rupture them, so strongly do many of them resist an attempt steadily to pull them apart. It is not infrequent to find machines used for such purpose weighing up to a ton or more, and there are several reasons for this. In the first place, the material is given a straight pull and not jerked or torn (unless special characteristics are in question). To achieve the slow extension up to the breaking load, heavy moving parts are necessary, particularly for example, with a 2 inch wide strip of heavy canvas or a parachute harness webbing that can sustain thirty cwt. dead load.

Historically, the pendulum machine was probably the earliest to be developed, followed by the steelyard beam system. Compound balance lever models were more recently adapted for textile work from their original use in testing metal wire and cables ; while some twenty years ago, when research on the subject was increasing rapidly in scope, the ballistic principle was exploited.

Pendulum Testing

Fig. XVIII. 1 shows a pendulum type horizontal cloth tensile strength tester built of cast iron and steel, to last almost indefinitely

with proper attention. Regular calibration, lubrication and replacement or trueing up of worn parts are essential. Cloth is tested in the form of strips cut from the piece in a predetermined scheme to achieve correct sampling. The specimens need to be about six inches longer than the distance between the jaws and they are cut a little wider than the specification requires so that they can have their side threads removed down to an exact measured width, leaving a fringe that prevents loss of yarn at the edges during the straining. Insertion of the specimens in the corrugated steel faces of the grips may have to be accompanied by soft cloth or other pads to prevent cutting in the jaws. Marks on the jaws assist correct placing of the strips, which are gripped by pulling the powerful levers over so that their cam-shaped lower parts force down the clamps.

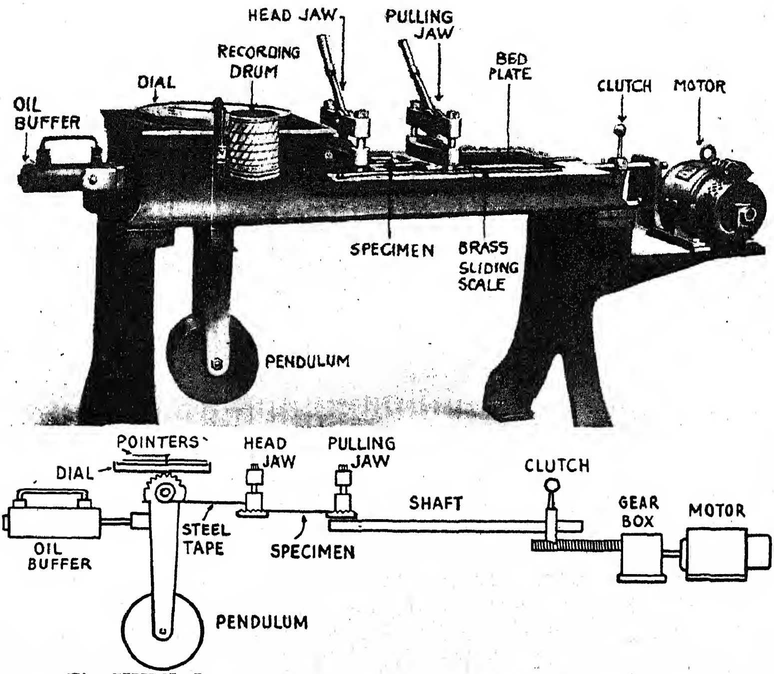

Fig. XVIII. I. Pendulum type tensile strength testing machine.

As an alternative to the usual width of strip of 2 inches for cottons or $6\frac{5}{8}$ inches for woollens, a 4 inch wide cutting is much favoured in America for the "grab" test, in which clamps an inch wide above the specimen and 2 inches below pull apart the body of the cloth with no edge effect. Results are higher owing to the support given by the yarns at the side of the area under strain. Tests can be

completed more quickly as there are no strips to prepare to an exact width, but accuracy is lost since the grab does not necessarily cover the same threads at each end of the section under test even when lines are drawn to guide the insertion of the sample in the jaws.

The sequence of procedure in breaking strips is first to insert the specimen in each jaw so that the tension on it is even and correct, and then to adjust the brass slides (one of which can be seen lying along the flat side of the machine in Fig. XVIII. 1) that register extension by travelling with the head jaw as the whole system moves along the bed plate, when the machine is set working by engagement of the clutch in the spirally grooved shaft. This shaft is revolving with the drive from a motor through one of the selection of gears usefully incorporated to give $4\frac{1}{2}$, 12 or 18 inches per minute traverse. Modern research advises the lowest of these speeds, since the inertia effect, due to the inherently jerky movements of the heavy pendulum as the cloth breaks down, is then at its lowest and, incidentally, the results more nearly approximate to those from a constant rate of loading. The higher gear, however, naturally allows more tests to be dealt with in a given time and is, therefore, difficult to displace from general practice and from specifications of long standing.

As the pulling jaw extends the specimen, it drags the head jaw with it, but much more slowly. The latter is attached to the pendulum by means of a steel tape, shown in the diagram of Fig. XVIII. 1, passing around its suspension and fastened to it so as to cause the heavy bob to rise and thereby act as an equal and opposite reaction to the stress. At the same time, it records the resistance of the strip to rupture by means of a small ratchet, which causes a pointer to move over the circular scale graduated in lbs., seen under a glass cover in the illustration in the figure. This pointer pushes a red painted finger which remains at the strength reached, while the other revolves back to zero when the pendulum swings down again.

These machines are conveniently made in capacities of 400, 700, 1,000 and 1,500 lb. Unreliable results may be expected if a pendulum type instrument is used for a test when its capacity is more than about ten times the breaking load of the specimen, or if the deflections of the pendulum are below approximately 9° or above 45° when the material is ruptured. This working range is governed by the relatively heavy mass of the pulling system and by the practicable height to which the pendulum can be raised. Machines of larger capacities may give slightly higher readings than smaller ones breaking the same cloth. The "machine rate of load" M (which is defined as the increment of load per inch of movement of the head jaw) varies with the angle of deflection of the pendulum : $M = P/r \sin \theta$, when P = dial reading, r = radius of tape drum in head of pendulum (see Fig. XVIII. 1), and θ = angular deflection.

It is quite possible for two machines having the same "machine rate of load" (e.g. 1,100 lb. per inch) at zero deflection and with the same jaw speed to have different capacities (i.e. different pendulum weights). The machines will also give dissimilar results on the same cloth.

The extension of the cloth strip at breaking point (as distinct from the elasticity, which is recoverable extensibility) is often a valuable item of information. It is recorded by a pointer fixed to the pulling jaw and travelling over the brass slides which were mentioned above and which move with the head jaw. The machine, further, is advantageously fitted with a revolving drum on a bracket at the dial end, recording the stretch-load diagram which is traced on a chart by an inked pen connected through a cord with the pendulum and from which the extension at any point in the test can be read off.

Balance Lever Testing

Alternative instruments, built to give capacities up to 8,000 lb. at constant rate of traverse, employ the principle of the balance lever and do not suffer from the restriction of limited working.

Fig. XVIII. 2 (a) illustrates this type of machine and Fig. XVIII 2 (b) shows the mechanical system from which latter it is clear how the machine may give constant loading on the specimen. The

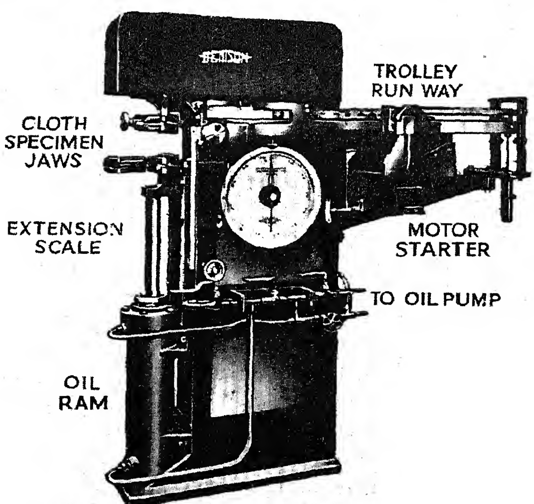

Fig. XVIII. 2 (a). Balance lever type double purpose strength testing machine.

machine may have a working capacity of 1,200 lb. per minute and is more automatic in action than the simpler, earlier types described later.

The specimen is attached by its upper end to the weighing lever system and by its lower end to the pulling system, which is actuated by transmission from an electric motor and pump forcing oil into and out of a ram.

There is no necessity for any measurement of this force, the load on the specimen being applied and weighed through the medium of knife-edged levers.

The grip holding the upper end of the specimen is attached (inside the casing at the top of the plant) to a knife-edge lever connected by a vertical link to another lever which serves a double purpose. It actuates the curved link shown working over the steelyard knife edge and also, by means of the lower vertical link operates the system that moves the dial pointer.

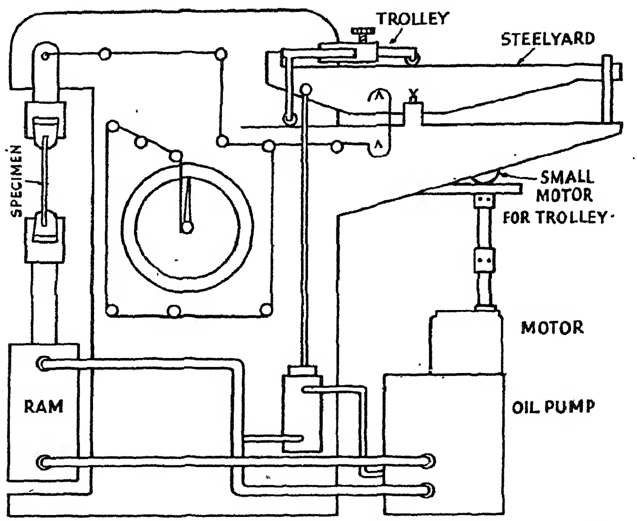

Fig. XVIII. 2 (b). Mechanical system of balance lever type double purpose machine.

The constant rate of load mechanism (covered by B.P. 560,832) comprises the trolley carriage, which travels along fixed rails. The trolley is traversed by a small motor seen in the diagram behind the steelyard. At zero position, the trolley rests against the stop on the steelyard and its front axle is then exactly over the steelyard knife edge, and so no moment is applied. The trolley travels at a steady speed, adjusted by the setting of the slide weight (the knurled knob clamping it) causing the load to increase at a constant rate. The

steelyard must remain floating with its outer end as a cantilever between stops. This would need no adjustment of the machine if the specimen were inextensible, but textiles always yield stretch which must be taken up, so the lower jaw movement is controlled automatically by a rod which connects the steelyard with a needle valve on the oil transmission system at the back of the frame of the machine.

At the front, in Fig. XVIII. 2 (a), can be seen the two handles by which the oil is made to raise or lower the ram when the specimen is placed in the grips. During the test the ram moves automatically. Also at the front is the scale recording the extension of the material at break or at an intermediate load. The hand wheel sets the rate of traverse, while on the right-hand side of the frame (just visible in the photograph) is a disc which, when turned, brings into action alternative knife edges and corresponding capacities on the dial in four stages, for instance, from 800 to 8,000 lb.

Grips of several kinds can be used on the machine, the choice naturally depending on the nature of the material to be tested. "Book type" jaws clamp ordinary light or medium cloth. Strips of heavy material or webbing are wound through slots in steel cylinders and lap round their circumference; while bollards, with grooves cut across intersecting at right angles, serve to hold cords which are laced round them for the test.

The constant rate of loading already mentioned in previous paragraphs is important, since certain large classes of materials, specially those for aeronautical purposes, are usually tested by steadily increasing the load instead of pulling them at constant speed. Fabrics of different texture, such as for aeroplanes, balloons, parachutes, or certain protective covers, for example, each require an individual setting of the machine, whereby at the end of a minute the specified load has been added. This is achieved either by means of the trolley just described or by the original earlier method of lead shot pouring into a bucket from a reservoir through an adjustable valve set with the aid of a stop watch.

Steelyard Testing

Simple machines of this kind, illustrated in Fig. XVIII. 3, embodying the principle of the steelyard, are still in use in many laboratories (although tending to be displaced by more automatic and totally enclosed mechanisms). The specimen is clamped at its upper end by jaws attached to the beam at a distance on the operating side of the knife edges so that the static moments about the support are, for example, 20 to 1. In the alternative model, seen photographed in Fig. XVIII. 3, the system comprises a chain passing over the flange of a similarly sustained disc resting on a knife edge at its central point of balance and with the specimen's upper grip suspended over

its axle. On the chain is attached the bucket into which the shot runs as soon as the valve is released. The moments on this model can be either 16 to 1, or 8 to 1 by altering the size of the axle and adding "distance pieces" at the side of the frame. Operations on it are not automatic, because the often violent extension of the cloth during application of the load has to be taken up by lowering the bottom jaw by the hand-wheel-operated pinion in order to keep the beam balanced. A fixed pointer and mark on the rim of the disc help this operation.

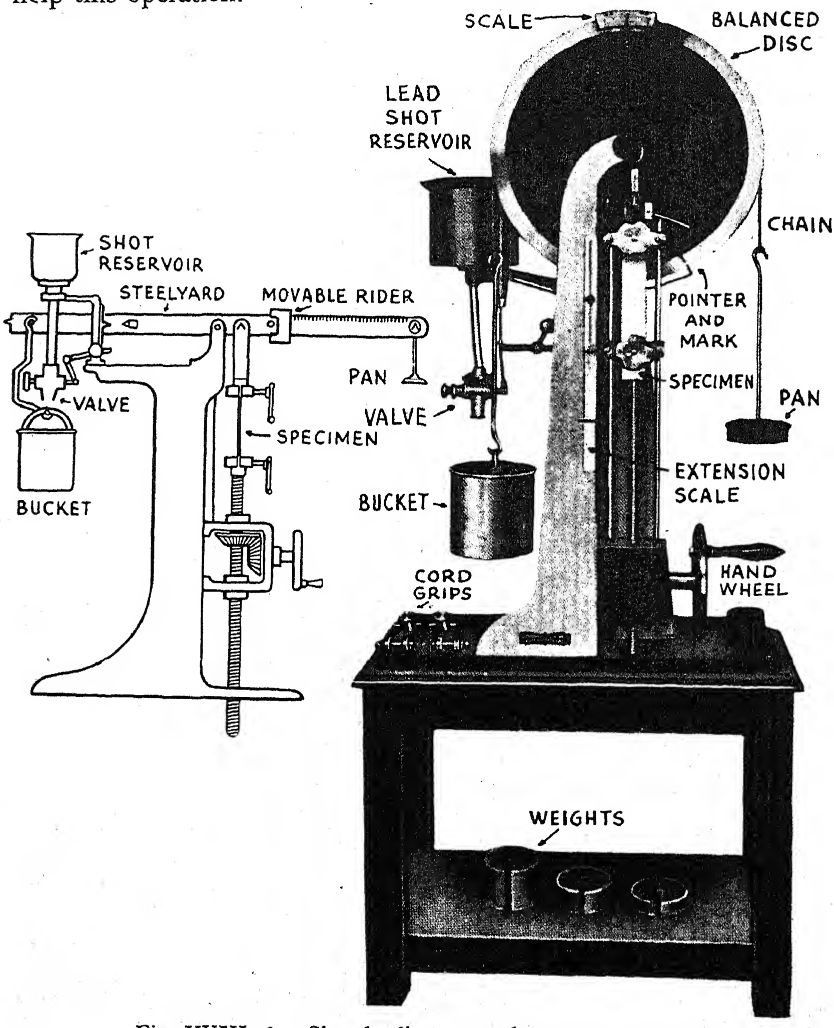

Fig. XVIII. 3. Shot loading strength testers.

As the specimen breaks and releases restraint, the beam tips or the heavy disc swings round to the left and knocks an arm which closes the valve. The amount of shot in the bucket is then determined by placing weights on the pan hanging from the free end of the beam until the balance is obtained. The last few pounds are registered on a small scale over the top of the circular plate of the disc machine. On the beam instrument, final adjustment of weight is made by a movable brass rider, up to 50 lb. The capacity of these machines is usually 250 or 500 lb, but compound lever straight beam models are in use working up to 3,000 lb.

The Inclined Plane

There are, of course, other types of strength testing instruments. Thus, one becoming more popular in America for relatively low loads, and used for yarns as well, employs the inclined plane method of applying the strain. One grip is fixed on the end of the plane, which is made to tilt by a motor, thereby causing a trolley, on which the other grip is mounted, to run down the slope, exerting a constant rate of loading on the specimen by putting steadily more and more pull upon it. Advantages associated with this system, in common with all the constant loading instruments, are the absence of the effect of size of machine as well as of length and extensibility of the specimen. The chief consideration is that the steady accretion of pull is achieved without the inertia difficulties of the pendulum.

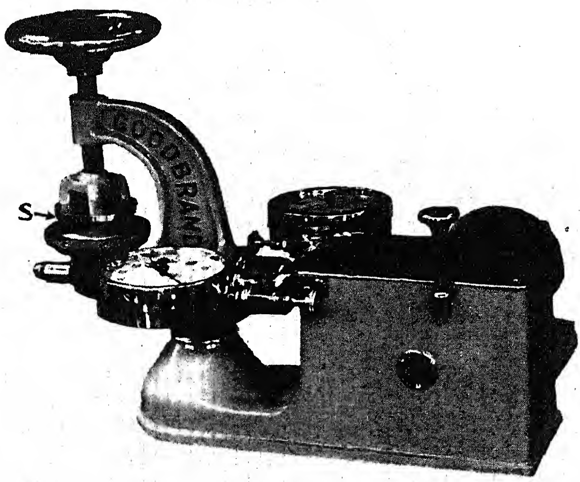

Fig. XVIII. 4. High pressure bursting tester for fabric, paper, etc.

Bursting Tests

An outline of fabric strength testers would not be complete without reference to instruments that sunder the material by bursting pressure exerted at right angles to the plane of the fabric instead of by pulling. It is a closely allied test, but is not easily correlated with a tensile result on the same cloth because the threads forming the more tightly woven direction of the material will probably rupture first. It is valuable when little cloth is available for examination, such as during investigation of defects.

The pressure per square inch necessary to burst the fabric is approximately inversely proportional to the diameter of the specimen. Small areas are generally used, the circular orifice having commonly a diameter of 1.2 inches. Well-known instruments give pressures up to 1,200 lb. per sq. in. The medium can be glycerine and the power is provided by motor or geared hand wheel. The illustration in Fig. XVIII. 4 shows where the specimen is placed under the vertical circular clamp supported by a thick rubber diaphragm, allowance for the latter's separate resistance being made by reading the gauge after exerting the same force as in the actual test.

A special form of bursting tester (Fig. XVIII. 5) is that used for cloths of low resistance or on a fabric after it has been punctured

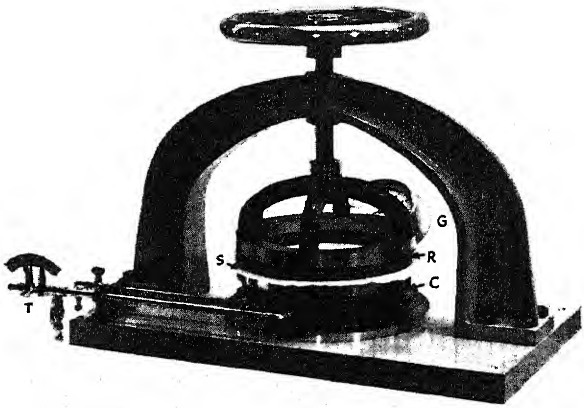

Fig. XVIII. 5. Low pressure bursting tester.

by a short cut (usually of $\frac{1}{2}$ inch) to imitate a rent caused, for example, by a bullet. A larger test area is used, such as 7 inches diameter, and the instrument is limited by the capacity of the rubber diaphragm to a gauge pressure of not much more than 30 lb. per sq. in. The fabric specimen (S) is stretched over a circular metal chamber (C) and held by a ring (R) pressed down on it by a bell-shaped clamp which is carried by a strong curved frame. Hydraulic pressure is

applied by water from the mains passing through an adjustable tap (T) into the chamber, under the diaphragm supporting the specimen, at a rate set to give a known slow increase of pressure, the final value of which at the moment of burst is registered by the gauge (G) connected to the water chamber.

Ballistic Tests

A model employing the ballistic method appears in Fig. XVIII. 6, and was designed by its originators, Midgley and Peirce, to test either yarn in the form of leas or narrow tapes of cloth. The specimen is attached at one end to one of the fixed clamps on the base board and at the other to a pendulum bob, while this is held by a trigger catch in the raised position. When the catch is released, the pendulum swings through its arc, pushing a pointer. This moves over a curved scale, but does not rise to the full height it would on the opposite side owing to the resistance offered by the breakage of the specimen, which takes place practically instantaneously. The work of rupture of the textile is read off the scale in inch, pounds, units, giving a combined measure of strength and elasticity.

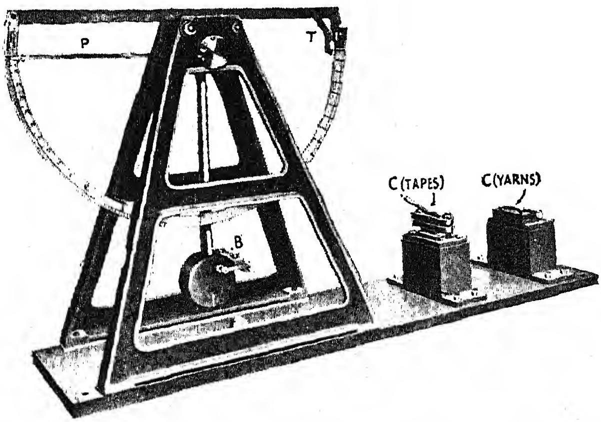

Fig. XVIII. 6. Ballistic testing machine. B, pendulum bob attachment. C, fixed clamp. P, pointer. T, trigger catch.

Yarn Testing

The testing of yarns has been mentioned several times in the preceding paragraphs when an instrument was being described that could deal with threads as well as cloth. Generally speaking, however, a more lightly built and smaller type of machine is employed for the purpose. Yarns are tested in two ways, either as single threads or in the form of skeins or leas. The highest capacity of lea tester ordinarily employed is 350 lb., although for most purposes

one reading to 100 lb. is sufficient. The latter capacity is usually high enough for single threads, too. Where very fine yarns of cotton, silk or rayon are concerned, machines to give a maximum loading of no more than 1,000 grammes are best employed.

In principle, the great majority of yarn strength testers incorporate the pendulum system and are vertical in build. This renders introduction of the single thread specimen easier, especially if it is to be inserted with a small weight attached, before closing the upper jaw, in order to ensure standard tensioning. It also enables a lea of 120 yards of yarn to be placed conveniently over the grips and spread out so that each thread of its 80 wrappings takes its strain equally. One or two detail points of difference from the cloth tester exist. In modern instruments the power is applied to the lower pulling jaw by a motor, but hand-driven models are still in use in which an oil-buffered falling weight supplies the motive force. Further, the general method of recording the load is for light catches or pawls on the arm of the pendulum, as it rises under the pull transmitted through the specimen, to ascend a toothed rack sector on which they catch and stop when the break occurs. Thus the pendulum remains stationary until released, and the corresponding position of the pointer on the scale gives the breaking load.

A recording textile extensometer is described in Chapter XIX.

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SECTION 6

RECORDING INSTRUMENTS

CHAPTER XIX

ELECTRICAL AND MECHANICAL RECORDING

Various types of recorders are so widely used for industrial, laboratory and research purposes, that it is impossible, in a short compass, to deal with the many investigations to which they may be applied or to give details of such processes, many of which are referred to, more fully, in other chapters dealing with specific applications.

The types of recorders in general use may be classified into

(1) Electrical Recorders (including electronic),
(2) Mechanical Recorders,

and they may be either

(a) Direct pen writing,
(b) Dotting (impregnated thread or ribbon),
(c) Iodide paper (Chemical change),
(d) Light beam (photographic),
(e) Stylus on Celluloid.

Electrical Recorders

The simplest form consists of a moving mirror galvanometer, a light source and a rotating drum photographic camera. The beam of light is projected on to the galvanometer mirror which deflects it, through an aperture in the drum camera, on to the photographic paper. The sensitivity is dependent on that of the galvanometer and the projection distance. Such simple recorders find application in laboratories for research purposes, but an example of more extensive employment is that used during the war, of recording fluxmeters for checking the demagnetisation of ships on entering and leaving ports, and thus rendering shipping safe against magnetic mines.

Another example is that of recording outfits for geophysical exploration. In this application a number of sensitive seismic units are placed at carefully surveyed distances apart and connected to sensitive quick period galvanometers recording on a photographic drum camera. An explosive charge is detonated in the ground and the percussion wave travels downwards until it is reflected by changes in strata density through various geological formations and returns to the surface. Here it is picked up by the seismic units and the different times of reception of the wave front accurately recorded. From these photo records it is possible to determine the depth and nature of the strata bands and the location of salt domes sometimes thousands of feet below the surface. These salt domes are often

associated with oil bearing strata and determine the best position in which to sink bore holes. These recorders are extensively used in America, Iraq and other oil producing territories.

Other photographic recorders include the many forms of high-speed reflecting mirror oscillographs for alternating wave analysis, etc., and the indirect photography of the cathode ray oscillograph screen. More detailed references to the applications of photographic recording are given in Chapter II.

The more common form of direct deflection recording galvanometer is the direct writing type in which the galvanometer coil carries a very light pen arm at the end of which is fixed a specially designed pen. The pen rests in light contact on a rotating drum around which a paper chart is wound. In such instruments great care is taken to relieve unbalance strain on the suspended system by counter

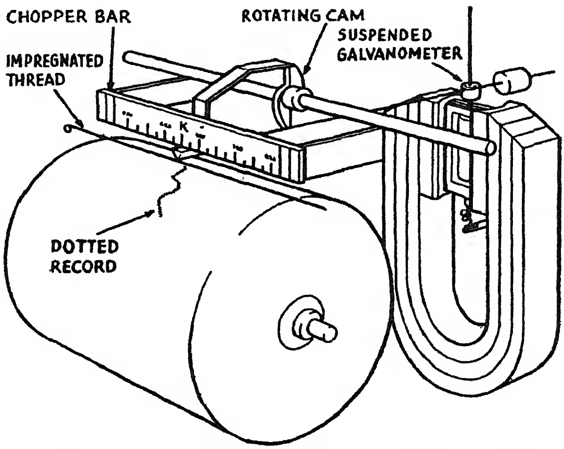

Fig. XIX. 1. Darwin's "dotting" or "thread" recorder.

weighting the pen arm. Such a direct writing instrument is not suitable for work of high sensitivity as the suspension must be sufficiently robust to carry the weight of the coil and pen arm and must have a high torsional control to overcome errors due to friction of the pen point on the chart surface; it does not therefore find use in most industrial or laboratory applications.

Such limitations have been largely overcome in the "Thread" or Dotting Recorder designed by Sir Horace Darwin in 1905. In this instrument, the pen point is replaced by a chopper which is periodically depressed by a chopper bar, operated by a cam mechanism, on to the rotating chart drum. Between the chopper and the paper is stretched an impregnated thread or ribbon so that a dot is made on the chart at each depression of the chopper bar. Thus the galvanometer

is free to deflect without frictional errors and its pointer is held stationary only at the moment of depression of the chopper bar. By employing a commutator and a frame carrying a number of impregnated threads of different colours with a mechanism for bringing them alternately into the correct position, it is possible to use one recorder for a number of different observations. The resulting record consists of a series of dots usually made each half minute, but it will be appreciated that any rapid changes that may take place between the dots are not recorded, a fact that limits this instrument to relatively slowly changing observations; nevertheless, it is still employed in large numbers for industrial and laboratory purposes, particularly for the measurement of temperature, CO_2 in flue gases and similar applications. Such direct deflection instruments cannot easily be employed for "set up" ranges, i.e. ranges that do not commence at zero but begin to record at some predetermined value. For such purposes a potentiometric recorder is usually employed. They may tend to be replaced by the more recent electronic recorder to be dealt with later.

Another method, devised by Professor H. Callendar in 1898, and incorporated in the well-known Callendar Recorder, also obviates the drawbacks of a direct pen writing system. Unlike the thread recorder, this instrument is not a direct deflection instrument but incorporates a boom, attached to the galvanometer moving coil, finished at the end with a platinum prong. This prong straddles a clock-driven revolving wheel that has a platinum rim. When the galvanometer is slightly deflected in one direction one arm of the prong will contact the rim of the wheel and close a circuit through a relay which releases a brake on a spring-driven pen mechanism, permitting it to travel over the paper chart. Thus the power required to move the pen is independent of the e.m.f. applied to the measuring unit. The pen carries a contact resting on a stretched slide wire which enables an e.m.f. of opposite polarity to be inserted in the galvanometer circuit and thus restores the balance of the boom; for example, if an e.m.f. of say 1 millivolt flows through the galvanometer, the boom will deflect and release the brake on the pen which will move along the slide wire until it reaches a position where 1 millivolt counter current is tapped from the slide wire, at which position the e.m.f. through the galvanometer will be neutralised and the boom will break contact and the pen remain stationary. When the galvanometer is deflected in the opposite direction, the second prong of the boom engages on the opposite rim of the wheel and operates a second brake mechanism which permits the pen arm to move in the reverse direction.

The range of the instrument is determined by the calibration of the slide wire and has a great advantage in that the scale is linear and may be very open. A further advantage is that the scale may

start at any predetermined value ("Set up" scale) which is particularly useful in conjunction with thermocouples or resistance thermometers for temperature measurement when an open scale is required over a restricted range at high temperature. The Callendar Recorder in its early form is not now made, although considerable numbers are still in use. It has been replaced by other potentiometric recorders, most of which employ a "scissors" mechanism for operation that does not differ greatly in fundamentals from the earlier potentiometric pattern. Fig. XIX. 2 illustrates a modern potentiometric recorder made by the Cambridge Instrument Co. Ltd.

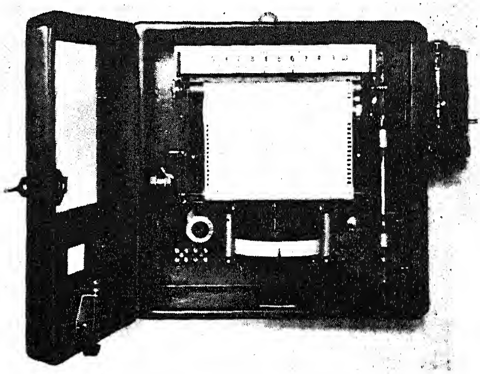

Fig. XIX. 2. Potentiometric recorder.

An alternative type of galvanometric recorder is that in which the record is made on paper impregnated with a mixture containing potassium iodide and starch. The "pen" or recording stylus is arranged to carry a small electric current which passes through the paper at the point of contact to a metal plate below. The current splits up the potassium iodide, giving free iodine; this combines with the starch to form the familiar deep blue starch iodide. Such recorders are usually used in conjunction with relatively insensitive short period galvanometers and valve amplifiers for recording transient effects such as occur in signals or pulses, in which case the recorder is employed as a chronograph. One considerable disadvantage is that the blue starch iodide record is not "fast", as the gradual vaporising of the iodide causes it to fade and finally vanish.

The limitations of the electrical recorders, already referred to, have been strained by increasing requirements for high sensitivity combined with speed of operation and robustness. This increase in sensitivity has invariably been obtained by the construction of more delicate and slowly operating (heavily damped) moving systems. This particularly affects instruments with commutator switching for multi-point recording, since time must be allowed for the galvanometer to take up a new steady position before the recording is made.

The introduction of fully stabilised electronic circuits has enabled weak electrical currents to be amplified to many times their original value and thus provide sufficient electrical power to operate relatively

insensitive and robust mechanical recording mechanism. Recorders embodying electronic principles have recently been developed and are now marketed. The advantages are obvious and this type of recorder may well become the standard instrument of the future for industrial applications. To describe one pattern will indicate the general principles of most designs.

These recorders are, in effect, null point balancing instruments, embodying an accurately calibrated potentiometer slide wire. The range is determined by the potential drop across the slide wire, the scale is linear whilst the normal accuracy is 0.5 per cent of the full scale reading. Single point instruments are pen writing, but a dotting recorder is also made for multi-point readings. The chart is usually of the flat circular type, but drum or continuous strip charts also are employed. The motive power which drives the slide wire brush and the pen is a two-phase A.C. motor. One phase is supplied directly from the A.C. mains, whilst the other is fed from the A.C. output of the amplifier, which is so arranged as to give a 90° lag or lead on the mains. Whether it is lag or lead depends on the direction of the e.m.f. which is fed into the amplifier. If the amplifier output is leading, the motor rotates in one direction, and if lagging in the other, thus moving the pen and slide wire brush which in turn feeds back to the input circuit an e.m.f. of opposite polarity until the balance is re-established and the pen remains stationary. Any change in input will move the pen in one direction or another until balance is restored.

The chart is rotated at a steady speed (usually 25 hours or 7 days duration). The speed of response is rapid and a movement of the pen across the entire scale is accomplished in 0.5 second, and the small changes are almost instantly recorded. Electronic recorders have the advantages of permanency of calibration, robustness, sensitivity, and rapid response. They may be applied to any process involving small direct currents such as occur in temperature measurement, gas analysis, pH measurement or other observations that may be obtained by the recording of fluctuating e.m.fs. A special type of electronic recorder is shown in Fig. XIX. 3.

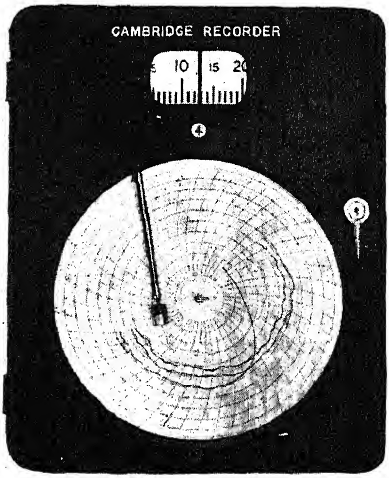

Fig. XIX. 3. Electronic recorder with 4 independent records on one chart. Note the bold illuminated indicating scale.

Mechanical Recorders

These instruments are made for so many purposes that it is only possible to refer to some of the widely used applications. Any problem that involves a record of a movement of one member in relation to another, or to a fixed point, can be determined by a mechanical recorder. Where such movements are small they can be magnified by lever arms or optical devices. They may be either pen writing or photographic, whilst one manufacturer specialises on a system of stylus on celluloid recording for very small displacements.

Among the more generally known mechanical recorders are instruments for the measurement of pressure. The prime mover consists of a bourdon spiral or aneroid vacuum chamber, which is affected by a change in applied pressure. In the case of the bourdon, the spiral tends to unroll as the pressure increases and the movement is transmitted by lever mechanism to a pen arm which moves over a rotating chart, which is usually of the flat disc type. These recording pressure gauges are widely employed in industry. In the aneroid type, the vacuum chamber either collapses or expands with pressure change, and the movement of the centre of the diaphragm surface is similarly connected by lever arms to a recording pen. An example of this type is the barograph, which records on a rotating drum, changes in barometric pressure. The vacuum chamber type is only applied for small pressure changes, but the bourdon spiral method is used for pressures up to 5,000 lb. per square inch. Temperature recorders may be similar instruments in which the bourdon is connected to a bulb filled with mercury or volatile spirit and hermetically sealed; changes of temperature expand or contract the mercury in the closed system and thus exert a pressure on the bourdon spiral proportional to the expansion occasioned by the temperature change at the bulb. (Fig. XIX. 4.)

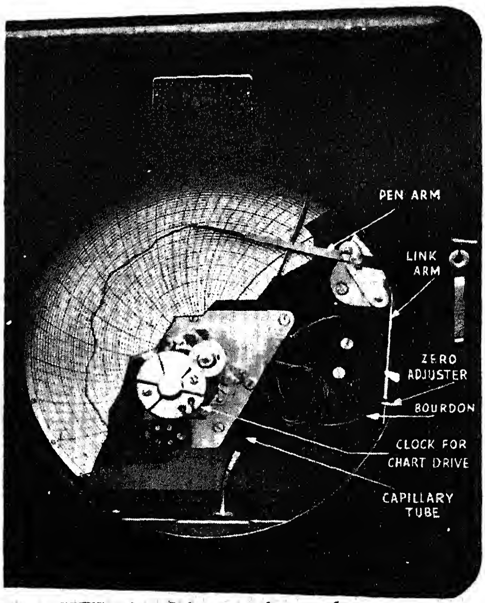

Fig. XIX. 4. Mercury in steel temperature recorder (Bourdon spiral type).

In such recording thermometers the bulb is

connected to the instrument by a length of capillary with a fine bore, this length may be up to 100 ft. long without exercising undue effects on the accuracy of the readings. The usual accuracy of such recorders is ± 1 per cent full scale reading, and they may be employed for temperatures up to 600° C., the limiting factor being the vaporising temperature of mercury.

Humidity Recorders

Similar recorders also are made for recording humidity in the atmosphere. In this case, the prime mover is a strip of gold-beater's skin or other material that changes in length in proportion to the relative humidity surrounding it. This gold-beater's skin is anchored at one end, whilst the other end is attached to a lever mechanism connected to the recording pen moving over a flat disc rotating chart. They are widely employed in drying sheds or in process rooms connected with the textile industry. The other humidity recorders consist of two mercury-in-steel temperature recording systems mounted in one case, and arranged to record the wet and dry bulb temperatures from which the relative humidity may be accurately calculated. (See also Chapter VI.)

In many industrial processes it is desirable to know the frequency of certain mechanical operations and recorders are employed for this purpose. Such recording counters will show the frequency, time of occurrence, and duration of an operation. The recording mechanism usually consists of an electro-magnet which is energised by the closing of a contact, made by the operation of the machine for which the record is required.

When the electro-magnet is excited it attracts an armature to which the recording pen is attached, thus causing a deflection to be made in the record. The pen remains deflected until the circuit is broken. Such recorders usually employ circular charts of either 1 or 24 hours duration and may be combined to operate along the edge of the same chart as temperature or pressure recorders. They are applied as machine running recorders, for the heat treatment of steel, boiler firing and as pump operation recorders, etc. A similar pen writing instrument is the chronograph which employs a paper band driven beneath pens actuated by electro-magnets. Such chronographs are employed for the determination of the reception time of wireless time signals and

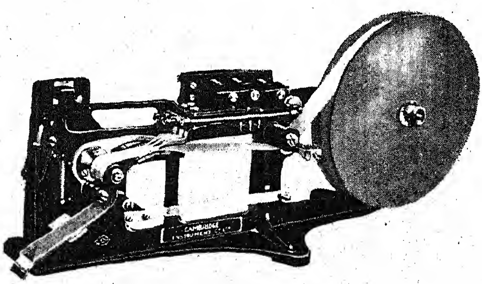

Fig. XIX. 5. Laboratory chronograph, 3-pen pattern.

comparison with standard clocks and similar applications. Fig. XIX. 5 shows a three-pen chronograph.

In connection with boiler fuel economy it is desirable to know the CO_2 content of the flue gases and recorders have been developed for this purpose. One system employs an electrical recorder usually of the dotting type already referred to, but an alternative mechanical type is also widely used. This instrument measures the differential pressure between the untouched flue gas and the same gas after it has passed through a soda lime absorption chamber which removes the CO_2. The chambers are arranged to float and take up different levels according to the CO_2 abstracted, and the differential displacement is proportional to the gas absorbed. A circular disc rotating chart with a direct writing ink pen is usually employed.

Another example of mechanical recording is the recording textile extensometer. This instrument records on rectangular co-ordinates the relation between load and extension of textile fibres, threads and yarns with increasing and decreasing loads. Included in the load-extension relationships are such factors as ultimate strength and extension and hysteresis loss arising from different behaviour during loading and unloading. The recording of a typical hysteresis loop is illustrated in Fig. XIX. 6.

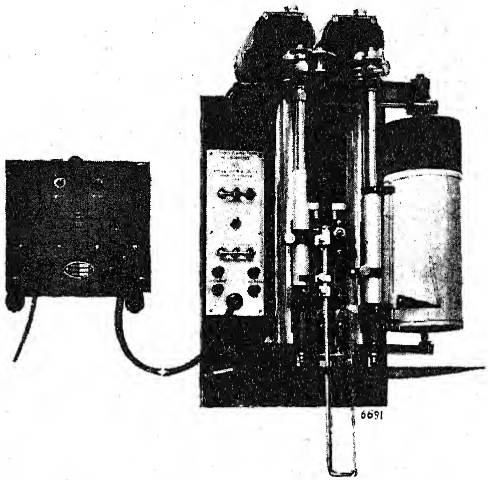

Fig. XIX. 6. Fibre extensometer for testing textile yarns.

The Seismograph

One of the most sensitive forms of mechanical recorders is a seismograph for recording earthquake shocks, often at great distances from the foci of disturbance. Briefly, these instruments consist of a heavy mass suspended in such a manner that, owing to its considerable moment of inertia, it will tend to remain stationary when the base or mounting is vibrated. By a series of delicate hinged couplings between the two components the small movements are made to rotate torsion suspensions on which a small mirror is fitted. A beam of light is projected on to the mirror and deflected on to the aperture of a rotating drum camera loaded with photographic

paper. The camera is so arranged that the drum is slightly displaced by a worm gear after each rotation so that a long record of considerable duration is obtained. Time marks are placed on the record by causing the light beam to be obscured for a moment, say, once each hour. An alternative form of seismograph devised by Prince Galitzin uses, instead of a mirror, a thin toroidal coil moving between the poles of a powerful magnet thus causing an induced current to flow in the circuit of a highly sensitive galvanometer, the deflections of which are recorded in a similar fashion. Seismographs are usually mounted on concrete foundations carried down to a solid rock base in the earth surface. They are made to record both horizontal and vertical displacements, and the mechanical magnification is as great as X 500. Earthquakes of magnitude are regularly recorded in this country even though the foci may be over 5,000 miles away. The seismic units employed for geophysical exploration, already referred to, work on a similar principle.

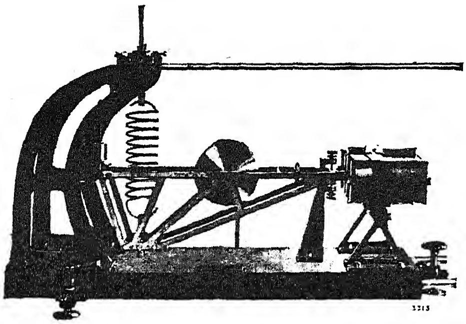

Fig. XIX. 7. Galitzin Seismograph for measuring vertical component.

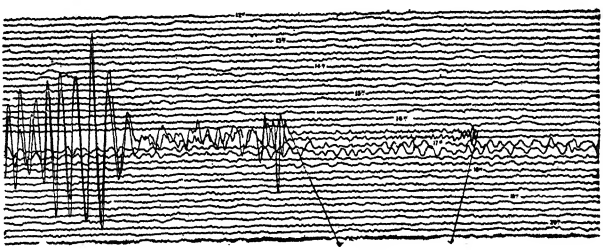

Fig. XIX. 8. Seismogram showing primary and secondary shock waves.

Combined Mechanical and Electrical Recorders

Many recorders are a combination of both mechanical and electrical principles. The prime mover may be a mechanical device whilst the actual method of recording is electrical. Among these are instruments for measuring the thickness of metal strip during processing on a rolling machine.

The strip or sheet leaving the mill passes between two roller jaws,

one of which is fixed whilst the other is floating. The floating member is coupled to the armature of an electric gauge, any movement of which varies the impedance of the magnet circuit and thus affects the deflection of an electrical recorder calibrated in terms of displacement.

These gauges are capable of recording variations in thickness of 0.0001 inch.

An alternative pattern consists of a pair of moving levers, linked together by a spring at their mid point and so arranged that their extremities bear on the rim of the roller and on the surface of the strip respectively, so that any relative movement is transmitted to a gauging device or electrical micrometer which consists of four identical spirals of platinum wire forming the four arms of a Wheatstone bridge. These spirals are heated and have the same electrical resistance. Any movement of the lever arms will cause an extension of two of the spirals and a contraction of the other pair. The extended spirals will lose heat more quickly and the resistance will be lowered, whilst the contracted spirals will increase in temperature and the resistance rise. This causes the bridge to become unbalanced and the amount of unbalance is recorded on an electrical recorder calibrated in terms of displacement. There are many variants of recorders embodying these or similar principles that have a wide field of application. They are very sensitive, accurate and quick acting, and may be applied as recording extensometers or as recording micrometers for any small continuous displacement.

Spectrum Analysis

The analysis of spectrum photographs may be carried out by means of Recording Microphotometers which embody photo-electric cells as the conversion medium. The spectrum photograph is placed upon a steadily moving carriage so that during its transit it moves beneath a light beam sharply focused in the plane of the photograph emulsion and the amount of light transmitted will be proportional to the density of the spectrum lines. The transmitted light is arranged to fall upon a photo-electric cell and the current generated will likewise be proportional to the density of the spectrum lines. The photo-electric current is fed to an electrical recorder which will provide a record in rectilinear co-ordinates of the position, width and density of the spectrum lines. These instruments are largely used for the spectrographic analysis of metals. Other forms of photo-electric recorders, also, are made for various purposes, but they all incorporate one or other of the electrically operated recording systems.

Stylus on Celluloid Recording

An interesting alternative method of mechanical recording is one that produces, on a celluloid surface, lines so fine and smooth that,

when optically magnified, readings accurate to about 0.001 millimeter can be made. The recording member is a stylus having a spherical end which is lightly pressed into contact with a moving celluloid strip. Plastic deformation of the celluloid surface occurs under extremely slight pressure and any movement of the stylus is accurately recorded. Instruments recording on this principle need make only very small movements and thus the controlling forces are relatively

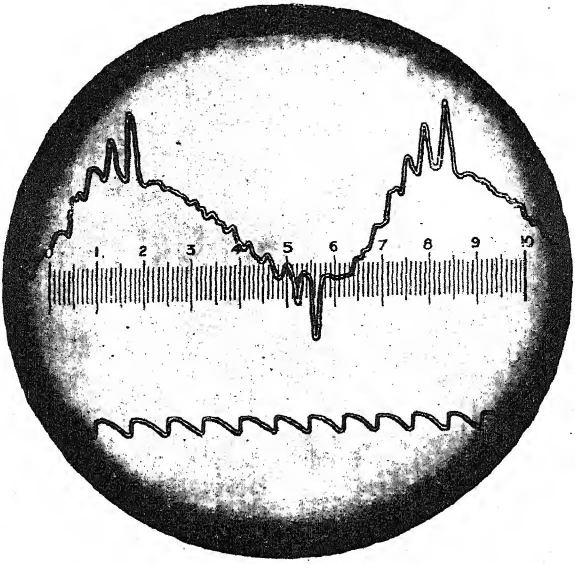

Fig. XIX. 9. Record obtained by the stylus on celluloid method: it indicates the vibration of a shaping machine during each cut.

great, and high frequency response can be obtained whilst inertia reactions are small. When the method is applied to the recording of fluid pressures the small movements necessitate only small volume changes and the reaction on the original pressure is negligible.

An interesting new application of this method is to record the camber of rolls of steel rolling mills. The camber is important if accurately flat sheets of metal are to be obtained from the mill as under the great pressure applied for rolling hard metals, the rollers themselves spring in the centre, and were they accurately parallel would produce slightly concave sheets. This camber recorder will determine the camber to 0.003 inch and the record is so compact that for a five-foot roll it measures only three centimeters long. Other recorders working on this principle are used for determining stress, vibration, displacement or for taking efficiency diagrams of internal combustion engines.

To conclude this chapter a few notes may well be made on the charts, pens and ink that are normally used with recorders of various types.

Charts. Most instrument manufacturers work to a limit of error of 1 per cent. One of the principal sources of error lies in the recorder chart itself and is affected by the accuracy of printing, quality of paper and effects of changes of humidity. Different applications and speed of writing each require special consideration. Considerable research has been carried out to arrive at the best conditions, and it is therefore always desirable to use the chart supplied by the instrument maker for each instrument. It should not be assumed that charts of the same dimensions are necessarily interchangeable. Unsuitable paper will cause the choking of the pen.

Pens. These are made in many forms, but for direct writing they are usually of a capillary type and are subject to difficulties due to choking by dust or paper fibres. They should be periodically cleaned by spirit, and a very fine wire passed down the capillary. Where the pen relies on capillary attraction up a groove to the pen tip, care should be taken not to distort the angle of the trough or to scratch the groove with a metal pin during cleaning.

Ink. Recorder ink usually consists of an aniline dye dissolved in water with an admixture of glycerine and other ingredients. It must be fluid, slow drying and non-corrosive. The fluidity is governed by the surface tension and is affected by change of temperature. The rate of drying or absorption by the paper is very important. If the ink dries too quickly it will tend to choke the pen, and if too slowly will tend to "feather" or spread over the chart thus making it too thick for a record for accurate readings, and will smudge easily when the chart is removed. These points have been fully investigated and suitable inks are made by most instrument manufacturers for specific purposes, and it is always advisable to use the ink that is recommended.

It has only been possible to refer to the more widely used recording systems. The many uses already are too numerous to be mentioned and new applications occur every day. Electronic recorders will open up still more spheres of usefulness, for many of the limitations of the earlier systems of recording have been largely overcome by this development.

CHAPTER XX

SOUND RECORDING

In the year 1857 Leon Scott de Martinville demonstrated that sound could be recorded by using a method of smoked paper on a cylinder. Unfortunately he had not thought of a method of reproducing these sounds and it was not until 1877 that real sound recording and reproduction came into being, through the genius of Edison who, using a cylinder covered in tinfoil, demonstrated that sound could be recorded and reproduced with quite simple apparatus. A few years later he developed the wax cylinder with which we are all familiar, firstly in the original Edison phonograph records and now in the modern office dictaphone.

In 1877 Berliner produced recordings on flat discs, instead of cylinders, probably with the idea, which actually came in some ten years later that it would be easier to produce copies in large numbers. About this time he also introduced the spring-driven motor in place of the hand-driven type used up to that time. Berliner called his machine the "Gramophone" and secured patents for it in 1888, a little later he evolved a method of making electrotyped moulds from which copies of the original recording could be pressed in soft material, afterwards being hardened for playing on the gramophone.

Electrical recording, as distinct from the earlier acoustic methods, was introduced in 1925, and with it came a considerable advance in the use of recording and in the quality of the results obtained.

Sound on film as we know it to-day was introduced about 1927, although Ruhmer photographed a sound track on film as long ago as 1900 with remarkable results. In 1918 Petersen and Poulsen used a mirror oscillograph for sound film recording and in 1923 Vogt and Masolle, and de Forest in America, were experimenting with variable density recording using gas discharge tubes. Modern sound film is used for so many applications in industry, educational and entertainment purposes, that it would not be possible to deal with them individually. Sufficient to say that modern equipment has progressed far, from the old days of Ruhmer and even the more recent introduction of sound on film, as against the older method of sound on disc synchronised to the film, and it is now possible to record and reproduce with a fidelity that leaves little, if anything, to be desired.

Magnetic recording was introduced by Valdemar Poulsen in 1898 with a machine called the "Telegraphone" using a heavy steel wire. Many experiments were made with this form of recording and probably the most practical machine to be used was the Blattnerphone and the commercial type of "Marconi-Stille" tape recorder as used

by the B.B.C. Little real progress appears to have been made during the past twenty years or so, and it was not until just before the war, in 1936, that the Germans introduced a form of recording using a tape with a magnetic coating, based on the patent taken out by Pfleumer in 1928. In 1939, both the Germans and the Americans began serious research into the possibilities of magnetic recording on wire and tape, and the results obtained have brought this method of recording to the forefront, both in the quality of reproduction obtained and the variety of uses to which it can be applied. Probably the most useful additions to the knowledge we have on this type of recording have been by the I. G. Farben Company in association with the A.E.G. Company in Germany, Marvin Camras of the American "Armour Research Foundation," and in this country, P. T. Hobson, whose researches into the magnetic properties of wire will have far-reaching effects on the future of wire recording.

The Microphone

A microphone is a device for converting sound waves into electrical waves, or currents, and may be considered as the counterpart of the human ear.

Of the many types available, the moving coil is perhaps the most popular. It consists of a light diaphragm, usually circular in shape, attached to the centre of which is a round former upon which are wound a number of turns of fine wire in the form of a coil. This coil is placed in the circular gap of a permanent magnet, the outer edge of the diaphragm being lightly fixed to the framework of the whole assembly so as to allow the diaphragm to vibrate in sympathy with the sound waves striking it. The movement of the diaphragm causes the coil to move in the magnetic field, thus generating an alternating potential across the terminals of the coil. The small electrical output thus obtained, the frequency of which in cycles per second (c.p.s.) is that of the original sound striking the diaphragm, is then stepped up by a transformer and fed to an amplifier of which the output power is sufficient to drive a recording mechanism of either the electro-mechanical or photo-electrical type.

The Dictaphone

This machine is probably the simplest form of recorder and is familiar to most people by reason of its use in offices for dictating purposes.

The recording medium is a cylinder of purified metallic soap, approximately 6½ inches long by 3 inches diameter, with a hole down the centre to allow of its being slipped over the mandrel which turns it during recording, at a speed of 98 revolutions per minute. The sound track is cut in the "wax" by a wedge-shaped sapphire cutter,

on the vertical or "hill and dale" principle with 180 grooves to the inch, giving approximately 10 minutes recording time. The average depth of the cut is one thousandth of an inch and a cylinder may be shaved and used some 40 times.

The machine consists of a heavy cast frame; on the underside is mounted a universal electric motor with the usual ball and spring governors. On the upper left-hand side is a casting with a ball race mounting for the mandrel, which is fitted in a horizontal position and has, on its end, a large pulley which is connected by means of a belt to a pulley on the shaft of the motor. Associated with the driven pulley is a simple clutch to enable the motor and its pulley to be kept running continuously, whilst the mandrel may be stopped and started for dictating purposes. The pulley mechanism is also used to drive a lead screw with a pitch of 180 grooves per inch. This lead screw is mounted parallel to the mandrel, as also is a slide bar upon which runs the carriage carrying the cutter head. A half nut on this carriage is engaged with the lead screw and so drives the cutter head from left to right across the cylinder on the mandrel, thus cutting a spiral groove on the cylinder from left to right. The cutter head may be either an acoustic or an electro-mechanical type.

Disc Recording

Commercial Methods. Recording machines for disc work vary very considerably in methods of general construction such as types of drive for the turntable and lead screw, but they all have one purpose in common with the high precision lathe which they so much resemble, that is to turn the material to be cut in an absolutely accurate and uniform manner from start to finish.

A commercial recording machine consists of a heavy turntable, mounted on a single ball and plain bearing, whose purpose is to rotate at a given speed with an accuracy of better than 0.1 per cent of the mean speed. Furthermore, it must not have any movement in a horizontal plane. Across this turntable is fitted an overhead carriage containing a lead screw, or continuous belt, to which is attached the cutting head in such a manner as to allow of its traversing the turntable from the outside edge to the centre, or vice versa. The carriage and turntable may be driven through suitable gearing by the same motor or by means of belts or rim drive to the turntable and a separate drive to the overhead mechanism. The cutter head carriage is so mounted as to allow accurate adjustment in weight on the cutting point to be made, also adjustments in the angle of the cutter as applied to the blank.

A wax blank, 14 inches in diameter and some $1\frac{3}{4}$ to 2 inches in thickness, is placed on the turntable, which is then made to revolve at 78 revolutions per minute. If the lead screw is then engaged and the cutter head lowered on to the wax, a spiral will be cut on the

wax, starting at the outer edge and finishing at the centre, or in actual practice some two inches from the centre, the lead screw having driven the cutter head along a radius of the disc, or wax, the pitch of cut used being between 96 and 112 grooves per inch. The size of groove cut in the original wax is of the order of 0.006 inch in width, 0.002 to 0.0025 inch in depth, and a radius of 0.0015 to 0.0025. These figures vary slightly with the different recording companies.

The cutter head may be either the moving coil or electro-magnetic type, and in either case a sapphire cutting point is used. During the cutting process a continuous thread of wax is removed, and if this is not disposed of it would foul the cutting point. Disposal is usually done by means of a suction pump with a tube fitted to the cutting head carriage, just behind and to the side of the cutter point, thus the swarf is sucked away almost immediately it is cut. The type of cut used in all commercial recording is known as the "lateral" cut and is illustrated in Fig. XX. 1.

Processing. It is usually desired to have many thousands of copies of the original recording. This is done by processing, which consists of coating the original wax with a fine powder of graphite, or more usually by "sputtering" gold on to the "wax" to give backing for the electrolytic process which follows. After the metallic surface on the "wax" has been built up by this process it is removed from the original and will be found to be an exact copy of the original recording, in the form of a negative. This negative is put into a nickel plating bath and a very thin layer of nickel is deposited on it, after which it is used to make a number of "mothers" in order that it may be safely stored for future reference, whilst the "mothers" are used for procuring, by similar means, a number of negative "stampers" from which the copies are pressed.

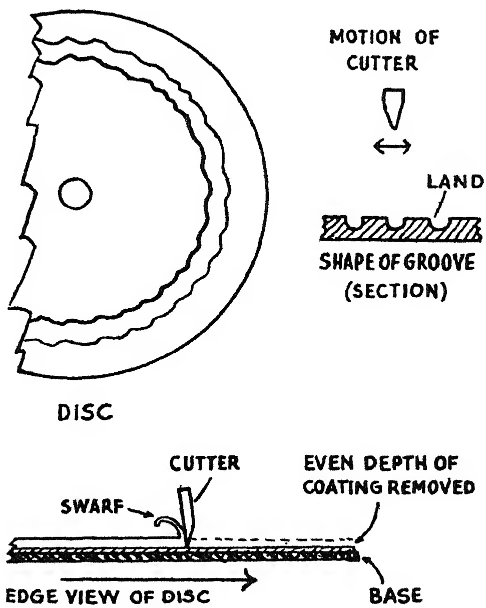

Fig. XX. 1. Lateral cutting method for gramophone records.

A "stamper" is placed in the top section of the press with another in the

bottom section; labels are put in position and the "biscuit" material, pre-heated and looking like a lump of dough, is placed on the bottom "stamper". The press is closed and a pressure of some 70 to 100 tons is applied, together with a circulation of steam; this is followed in a matter of seconds with cold water and in less than one minute the press is opened and the record is finished, complete with labels and only requiring the overflow material to be removed from the edge and a final polishing. It is said that a mark on the original "wax" only 0.00002 inch can be faithfully reproduced after going through all the stages in processing just mentioned, so accurate is the processing.

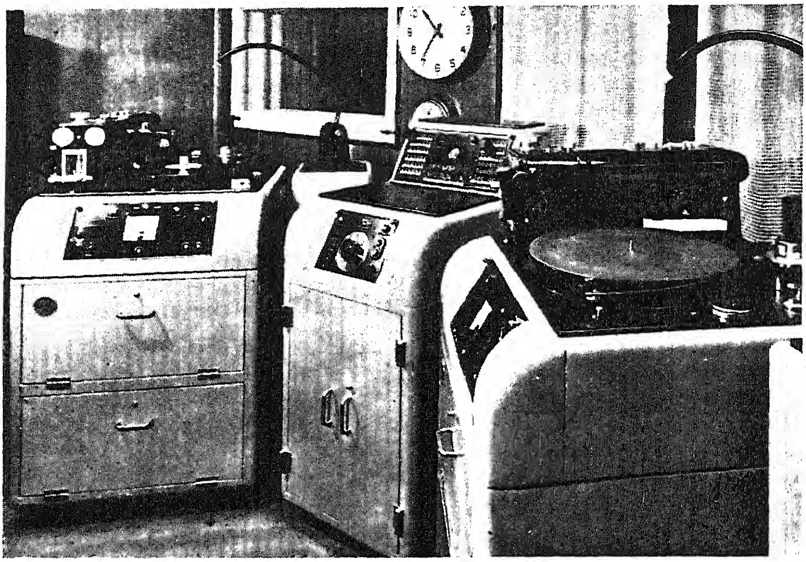

Fig. XX. 2. B.B.C. type 'D' direct recording equipment. Complete dual channel with control desk.

Direct Disc Method. The essential difference between commercial and direct disc recording is in the "blank" used for the original recording. In the former, a delicate "wax" is used for the express purpose of being processed for the production of copies and it cannot be played back immediately without damage. In the latter method the "blank" is produced with the intention of immediate playback for upwards of fifty times, without processing. The "blank" consists of an aluminium, zinc, or glass base upon which is coated a lacquer, having cellulose nitrate (celluloid) as its main ingredient, to a thickness of approximately 0.006 to 0.007 inch. This lacquer is cut by a sapphire cutter, having a tip radius of between 0.0015 and 0.0025 inch, in the same manner as the commercial "wax", the constituents of the lacquer being such as to allow of an easy cut, whilst having

sufficient strength to permit immediate playback with a long life. With correctly designed equipment it is possible to record a frequency range of the order of from 25 c.p.s. to 12,000 c.p.s. with a dynamic range of some 45 to 50 decibels.

The machine upon which the "blank" is cut varies from the fully professional type, similar to the commercial "wax" machine, to the light portable type used by the home enthusiast. In between these two extremes several excellent machines are available for private studios and broadcast work. An example of the highest class of workmanship may be seen in the new equipment designed by the B.B.C. and shown in Fig. XX. 2, whilst a first-class equipment for studio or semi-professional requirements is shown in Fig. XX. 3.

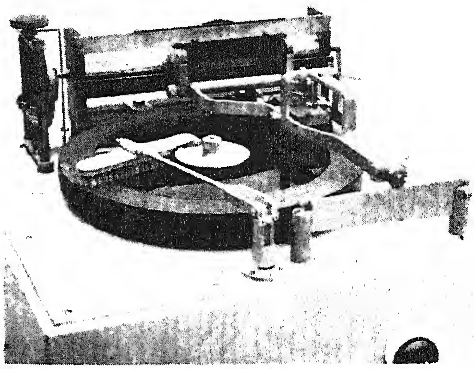

Fig. XX. 3. M.S.S. direct recording machine, studio type. Note brush for removal of swarf.

The main essentials of a direct disc machine are the same as in the commercial "wax" machine; several variations in the drive to the overhead lead screw are found in direct recording machines, and a very clear example of the type using a drive from the centre pin of the turntable is given in Fig. XX. 4.

The swarf cut from a direct recording "blank" is electrostatically charged and tends to cling to the disc, requiring more drastic methods

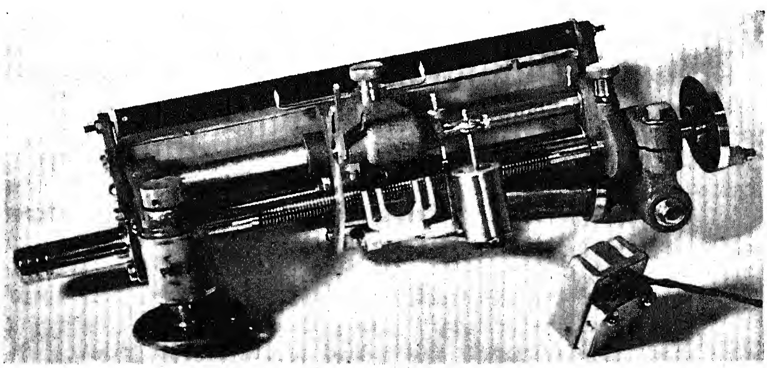

Fig. XX. 4. Centre drive and lead screw mechanism. Cutter head removed, at right-hand front.

of removal than the "wax" type of recording blank. This may be effected by means of the suction pump principle or by the use of a brush fixed on an eccentric arm causing it to sweep the "blank" as it revolves and so collect the swarf in a small pile, keeping it away from the cutter head. This brush can be seen in Fig. XX. 3.

The cutter head used is usually of the electro-magnetic type, a good example being shown in Fig. XX. 5.

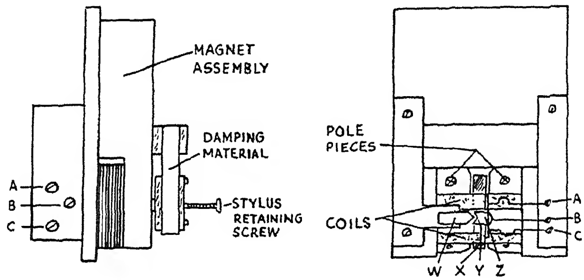

Fig. XX. 5. Balanced armature cutting head.
(Left) side view, showing damping block.
(Right) back view, showing armature pivot details.
A, B, C, screws for retaining springs.
W Knife edge.
X Stylus holder.
Y Armature 'V' slot.
Z Armature saddle.

Embossed Method. In this method of recording no material is cut, or otherwise removed from the blank, but the sound track is embossed, burnished or indented into the blank material, using the lateral method. The resulting track is in the form of an indentation with small ridges on each side produced by the material's having been pushed aside. A round pointed sapphire embossing tool is used, with a pressure of some 7 ounces, on to the blank material which is usually one of the plastic family with a cellulose base. The system may be used very successfully for long playing monitoring requirements as there is no swarf removed and the recording operation requires little or no attention, once correctly set up. A loop of fifty or sixty feet of 35 millimetre film may be fed through a normal type of sprocket-drive mechanism, and over a metal roller or skid shoe to form a solid foundation for the embossing tool, which, with a correctly designed lead screw, may be made to emboss approximately 100 tracks across the width of the film. As an alternative method a 12-inch disc may be used and the track embossed in the form of a spiral in the same way as the ordinary gramophone record. If a constant groove speed is maintained and a lead screw of 180 grooves to the inch a playing time of some thirty minutes is possible on a 12-inch disc. Embossed recording is not capable of a frequency range of

much more than 100 c.p.s. to 5,000 c.p.s. and is therefore more adaptable for speech recording than for musical work or other high quality requirements. The life of the record is fairly short, of the order of twenty or thirty playings, and the background noise is higher than with the cutting method, the dynamic range being not more than 30 decibels.

Sound on Film

There are three major types of sound on film recording; one a photo-mechanical method, and two photo-electrical, of the latter one uses a variable area system while the other uses a variable density system. In the photo-electrical methods a spot or beam of light is so arranged as to expose a track 0.1 inch in width on the film which is moving at a speed of 90 feet per minute. The modulations are represented by the amount of light which the developed film will allow to pass through on to a photo-electric cell during the reproduction stage. The amount of light may be controlled in one of two ways; the area of the transparent part of the track may be varied in width by allowing the light beam to expose more or less of the film; or the track may be exposed, constant in width, but with a variation in density of exposure. The former is termed the variable area method, and the latter the variable density method.

Variable Area. Referring to Fig. XX. 6, the image of the filament of the lamp appears on the mirror of the recording galvanometer, and a mask is placed near the condenser lens having a suitable aperture of correct size. A second lens produces an image of the aperture on the light slit. If now, the galvanometer mirror is caused to move by reason of the speech currents passed through the galvanometer, the

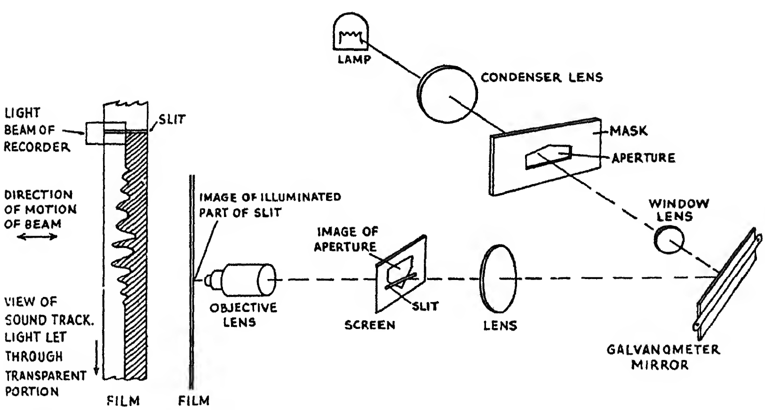

Fig. XX. 6. Diagrammatic view of variable area film recording, optical arrangement.

image of the aperture on the slit will move up or down, allowing more or less light to pass through the slit on to the film via the objective lens. In reproduction, a beam of light of the correct width is focused by suitable lenses on to the sound track of the film, on the other side of which is a photo-electric cell. The amount of light falling on this cell is controlled by the amount of sound track which has been exposed.

Variable Density. A gas discharge tube having a steady striking voltage is used in this method of recording. Speech signals are fed to the tube which vary the amount of light around the mean value. A condenser lens and light slit, as shown in Fig. XX. 7, are used to produce the light image on the film, which is arranged in the same manner as in the variable area system.

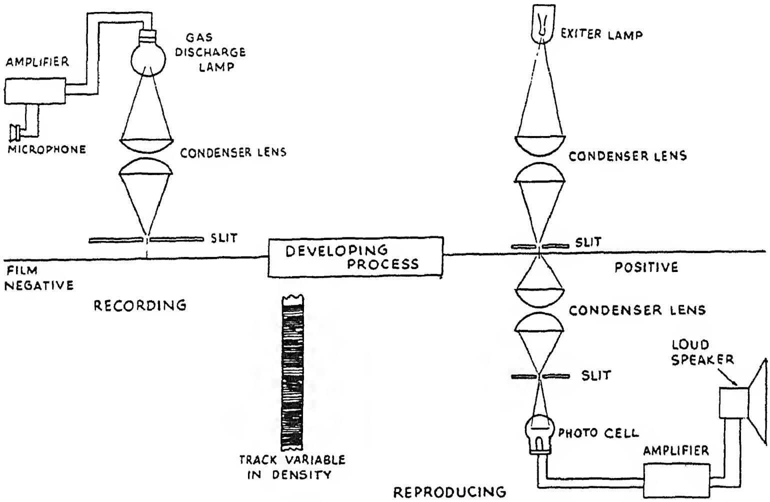

Fig. XX. 7. Diagrammatic view of variable density film recording, optical arrangement.

A second method of variable density recording is the light valve method. A constant source of light from a lamp is focused on to the slit of a light valve, and an image of this slit is then focused on to the film by a condenser lens in the usual manner. The light valve is essentially a loop of duralumin tape stretched tight, the centre portion being held by insulators to form a slit of the correct size, 0.001 inch. The loop is placed in a magnetic field in a position at right angles to the flux. When a current is passed through the loop it will cause it to open or close like a shutter, thus allowing more or less light to pass through it on to the film, which will be exposed to a varying degree, dependent upon the amount of light passed through the slit.

Photo-mechanical Method. An example of this method may be seen in the Phillips-Miller recording equipment used by the B.B.C. and other broadcasting organisations. It is capable of a very good frequency range, of the order of 50 c.p.s. to 10,000 c.p.s., with a dynamic range of 40 to 45 decibels, and may be reproduced without processing. A narrow film, 7 millimetres in width, is used, which is coated with a black emulsion to a very finely controlled depth. This emulsion is cut by a sapphire having a specially shaped tip which produces a sound track very similar to that of a variable area photographic track, and which is reproduced by ordinary photo-electric methods using a light beam and photo-electric cell. The film passes the recording head at a speed of 60 feet per minute, giving a recording time of 15 minutes with one loading. The film is costly, being about 55/- per quarter of an hour's recording, on pre-war figures. The equipment is delicate and requires a highly skilled operator for the best results to be obtained. Nevertheless, for high quality musical recordings with reasonably long duration it is in the first rank of recording equipments, particularly where immediate playback is desired without processing or other preparation.

Magnetic Recording

Magnetic recording may be done with steel tape or wire, or with a tape of plastic material or paper coated with a magnetic powder. Several methods of magnetising the recording medium are in use, but they are all the same basically. An erase, or wipe out head, usually precedes the recording head ; they are coils with soft iron cores held in contact with the tape or wire. Any variation in the current flowing in the heads causes a change in the local magnetic condition of the wire or tape, thus magnetising the medium used to a greater or lesser degree. Previous to the recording head is the wipe out head, which has a steady current flowing in its coil which demagnetises the tape completely. A tape with an audio frequency recorded on it will induce e.m.f's. in the coil of the reproducing head as it passes over the gap in the head, and these e.m.f's. may then be amplified in the usual manner. The latest development in this technique is use of an alternating current for the wipe out head of the order of 40 kilocycles in place of the more usual direct current used in the old Blattnerphone and similar machines. Alternating current is also used for "biassing" the recording head, of the order of 80 to 100 kilocycles and is fed into the head, the audio signals being superimposed upon it.

Wire Recorder. Many types of wire recorder have been produced in America, but only one in this country. This is a copy of the American Armour model 50, with several improvements. Wire of 0.004 inch diameter, carbon steel, or in later types specially heat

treated stainless steel or other special wire, is threaded from a full reel on the left of the machine, containing two miles of wire, through a wipe out head, a recording/reproducing head, and on to a drive pulley which pulls the wire off at a speed of either $2\frac{1}{2}$ feet per second or 5 feet per second as desired, the latter speed being capable of a greater frequency range, 150 c.p.s. to 4,000 c.p.s., than the slower speed, 150 c.p.s. to 2,500 c.p.s. Total recording time is 30 minutes for the high speed and one hour for the lower speed. Due to the fact that the wire is driven at a constant angular velocity, the speed through the head varies with the diameter of the take up reel, so that the machine is not capable of "wow"-free reproduction or the satisfactory reproduction of music or sustained pure tones. It is, however, excellent for most speech recording purposes. Other machines are in course of development using a constant linear speed drive which will overcome this disadvantage and which should be capable of good musical recording and reproduction. A useful feature of magnetic recording is the fact that any, or all, of the recording may be erased immediately and without affecting the remaining part. A disadvantage is that the wire must be re-wound before playback is possible, and although the machines are equipped with a re-wind action some time must elapse before playback is possible, usually about a third of the recording time.

Tape Recording. Just before the war the Germans introduced a tape recorder which reached a high degree of perfection during the war. A plastic tape of polyvinylchloride, 6.5 millimetres wide, is coated with red magnetite (Fe_2O_3) a few microns in thickness. This tape can be easily handled, cut, joined or otherwise edited as desired. Several types of machines have been developed, for various specific purposes. The one capable of the highest quality and used for broadcast work is the model HTS which has a tape speed of 77 centimetres per second, a reel of tape lasting some 22 minutes of recording and capable of a frequency range of the order of 50 to 9,000 cycles per second $\pm$ 3 decibels and a dynamic range of at least 55 decibels. A later type, K.7, was being developed at the end of the war, and it is understood a few models are available for experimental use. Three heads are used, basically the same, only differing in the gap size and the impedance—erase, record, playback, in that order. A capstan type drive with pinch wheel is used to drive the tape at a constant linear speed through the head assembly, a powerful electric motor being used for the main drive with smaller motors for driving the take up reel and the re-wind reel (Fig. XX. 8). A very complete treatment of the basic principles involved in the Magnetophon, together with a complete survey of the different types of instruments, may be found in *The Magnetophon Sound Recording and Reproducing System* by M. J. L. Pulling, published by H.M. Stationery Office, B.I.O.S. Final Report No. 951.

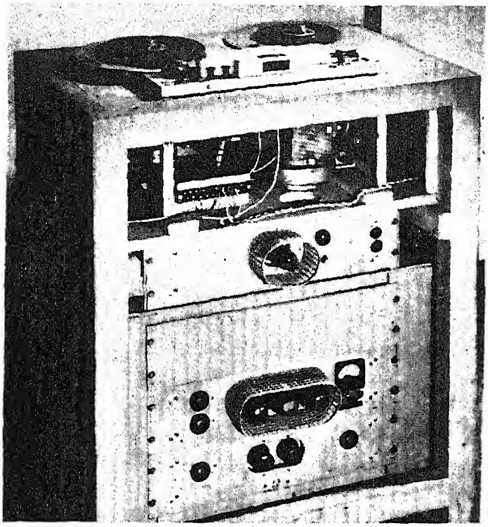

Fig. XX. 8. Magnetophon type HTS, tape spools and heads on top, drive and amplifiers on first and second shelves.

The Future

The very great uses to which sound recording has been put during the war have more than justified the large amount of development work put into all types of recording and have shown to what extent the science can usefully be employed in modern life. There is no doubt but that considerable improvements are even now being effected especially in magnetic wire and tape methods, and also disc, and it would be fair to say that in a very short time the amateur cine enthusiast on the one hand and the hospital and research laboratory on the other will benefit by having the use of magnetic sound film without the need of processing and the consequent long wait for results. The entertainment and educational world will have full range disc recording without any background noise for shorter works, whilst for the longer recordings a wire or tape machine will provide all that is required, even to a home recorder which will record a radio programme for the man who has to be away at the actual time of transmission.

Machines for operating timing and counting devices and for announcing the various stops or stages on trains, etc., and the floors served by lifts in large stores are already past the experimental stage. Obviously, we may expect many more applications of recording to our daily lives in the future.

Some applications of sound recording in the teaching of foreign languages are of course already well known and are conducted on quite a useful commercial scale. There are, however, aspects not so readily apparent which may be seen in operation at such an institution as the London University School of Oriental and African Studies. Here, in an effort to diagnose exactly sounds in oriental languages extremely difficult to the European ear and tongue, investigations are being conducted by accurately recording these sounds as visible wave forms in a fine powder on a cylinder and even by means of the cathode ray oscillograph and as a sound track on a special gramophone disc. These recordings are used for research purposes in conjunction with photographs of artificial palates on which certain tongue movements are recorded in French chalk. Photographs of the palate are then compared with the visible and measurable track of the sound waves and a disc record of the actual sound. By such means not only Europeans but sometimes orientals themselves are enabled to analyse the physiology of vocal sounds that would otherwise defy analysis.

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SECTION 7

MISCELLANEOUS

CHAPTER XXI

SHIP MODEL TESTING

The use of the experiment tank for testing models of proposed ship forms has become normal practice during the past thirty years. Indeed, few naval architects to-day would proceed with the construction of a ship hull which embodied any novel features without first having their probable effects explored by means of a model test. As an example, the final hull form adopted for the *Queen Mary* was based upon about 8,000 experiments made with no fewer than 22 models each 16.67 feet long. Experiments with hull forms of this type are the exception rather than the rule. The majority of work passing through an experiment tank has to do with coasters, tramps, tankers, tugs, trawlers, ferries, refrigerated ships and intermediate cargo liners. On occasion, however, extensive research has been carried out on such diverse forms as the lowly canal barge, the high-speed motor launch, the sailing yacht and even the single sculler and university "eight".

The purpose of a model test is usually to estimate the resistance of a ship form, the efficiency of the proposed propeller and hence to estimate the size of engine necessary to obtain a given speed. Other tests carried out help to estimate the wind resistance of the superstructures, the rolling, pitching and heaving characteristics of the ship, the efficiency of the rudder and the braking capacity of the propeller. Most experiment tanks are equipped with a wavemaker and experiments can be made under conditions similar to those encountered by ships in service. Models of the units of the Mulberry Harbour were all tested in waves during the early design stages. Such tests consisted of finding the best form for the units to act as breakwaters when moored in a rough sea and also to find the form best suited for towing across the English Channel.

Historical

Early experiments in the field of fluid resistance to a body in motion were not concerned with applications to ships but rather with problems concerning planes, spheres and other mathematical forms. The acknowledged pioneer in the ship model testing field was William Froude. Son of a Devonshire country parson, he was born in 1810, educated at Westminster School and later at Oriel College, Oxford. Later he was apprenticed to a civil engineer and subsequently he became assistant to the distinguished I. K. Brunel. With Brunel he was associated with many civil engineering projects

and eventually with the design and construction of the steamships *Great Western*, *Great Britain* and *Great Eastern*, the latter being the largest vessel of her day. In 1846, Froude retired from professional work and devoted himself seriously to model experiments. He carried these out in various places, some near his home on the River Dart, some on the lake at Keswick and some small scale work in a large storage tank at the top of his house. Many of these experiments were concerned with rolling of ships and the publication of this work by the newly-formed Institution of Naval Architects led to his association with many of the leading naval architects of his day. The chief constructor of the Royal Navy, Sir Edward Reed, who had visited Froude at home and saw his experiments with ship models, suggested that he should make a statement of his ideas to the Admiralty and express his willingness to carry out experiments on naval vessels. This he did and, strongly supported by Reed, their lordships reluctantly made a grant of £2,000 to construct and operate an experimental tank for two years and to explore exhaustively the whole field of ship model testing !

The tank was built in 1871 at Paignton and Froude began the series of resistance experiments which made his name world famous. The justification of his ideas came when in 1874 he was permitted by the Admiralty to conduct full scale experiments with H.M.S. *Greyhound* for the purpose of measuring her resistance when towed by H.M.S. *Active*. He showed that this full scale resistance could be reliably estimated from his model experiments and since that day the utility of model experiments has not been seriously questioned. It is of interest to note that Froude was 61 when the experiment tank was built and, during the remaining eight years of his life, he examined almost every aspect of ship resistance and propulsion, and laid down a programme of research which even to-day has not been completed.

The Experiment Tank

Froude's original tank was 278 feet long, 36 feet wide and 9.5 feet deep. At the present time there are some thirty experiment tanks in the world. The average length of existing tanks is about 500 feet. Recent tanks are much longer than this to cope with high-speed experiments. The largest tank is the American High Speed Basin which is 2,968 feet long, and models can be towed at speeds up to 110 feet per second (75 m.p.h.).

Fig. XXI. 1 shows the Alfred Yarrow Tank at the National Physical Laboratory, Teddington. 500 feet long, 30 feet wide, with 12.5 feet depth of water, this tank has been in almost continuous operation since it was built in 1910. There is a wavemaker at one end and a sloping beach at the other to prevent waves from being reflected back along the tank. A carriage, weighing 15 tons, spans

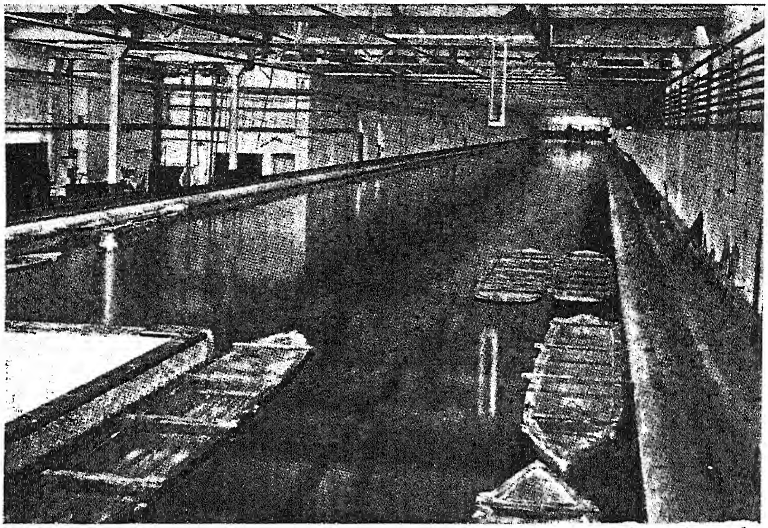

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Fig. XXI. 1. Alfred Yarrow experiment tank.

the tank and runs along the rails at either side. These rails are aligned as near level with the water surface as human ingenuity can measure. They were ground in position and legend says they could be used to measure the curvature of the earth. The slightest speck of rust on the rails can be detected by variations in the records of the delicate dynamometer fitted to the carriage and one man is employed continuously to keep the rails clean. The carriage is

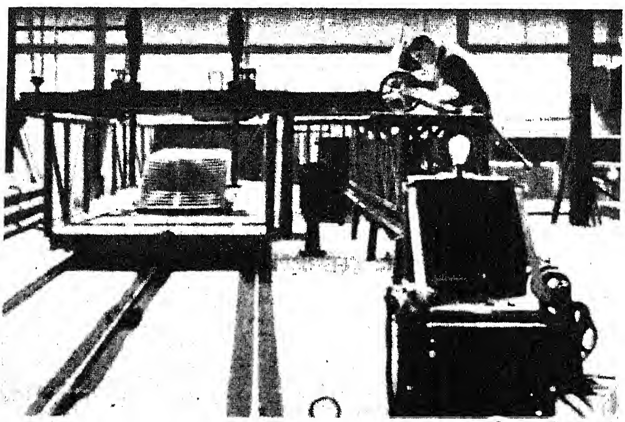

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Fig. XXI. 2. Wax model shaping machine.

driven by electric motors which pick up current from conductors along the wall of the building and speeds up to 25 feet per second can be achieved. Carriage running is usually at a constant speed, and any required speed can be pre-set and maintained with an accuracy of $\pm$ 0.01 foot per second. Because of this requirement the electric current is taken from large storage batteries, the ordinary electric mains not giving a current which is constant within the degree of accuracy required.

Model Making

Ship models are usually made about 15 to 20 feet long. In Britain the material used is paraffin wax and such a model will retain its shape for some months. In many other countries, because of excessive temperature variations, models must be made of wood if their shape is to be maintained over any period of time. A wax model is cast roughly to shape in a clay mould, the wall thickness of the model being about $2\frac{1}{2}$ inches. After casting, the top is trimmed level and this serves as a datum for subsequent shaping. The model is then floated out of its mould, turned upside down and put in the shaping machine. This machine cuts, in effect, horizontal contours of the exact scale form at about every $\frac{3}{4}$ inch of the depth with an accuracy of about ± 0.01 inch. Fig. XXI. 2 shows a model being cut. The model is then put on stools and the surface is scraped down to the contour lines with draw knives, spokeshaves and steel scrapers. It is then weighed, transferred to the tank, ballasted to the required draught, and is ready for resistance testing.

An ordinary wax model weighs about one ton when ballasted to its marks. A few exceptionally large models have been made for special experiments, the largest being 42 feet long and weighing $4\frac{1}{2}$ tons. The whole process of making a wax model occupies about four working days as against about 12 days for a wooden model.

Resistance Tests

The model is floated underneath the carriage and is attached to the dynamometer by a towing rod. This is the sole constraint applied except for two guides which maintain the model in a fore and aft direction. Thus the model is free to roll, trim or heave, and, indeed, may execute any motion except yawing. Fig. XXI. 3 shows the dynamometer. This automatically records the resistance of the model in pounds, the distance run by the carriage in feet and an electric clock records half seconds, and from these records the towing speed may be calculated. The model is run over a range of speeds and from the results of the experiments a resistance-speed curve may be drawn. From this curve it is possible to estimate the resistance-speed curve of the ship.

One advantage of the use of wax models is that desirable modifications to hull forms may quickly be tested, since all that is necessary is to add plastic wax to the model surface and re-cut in the shaping machine. Modifications to the form of wooden models require much more labour.

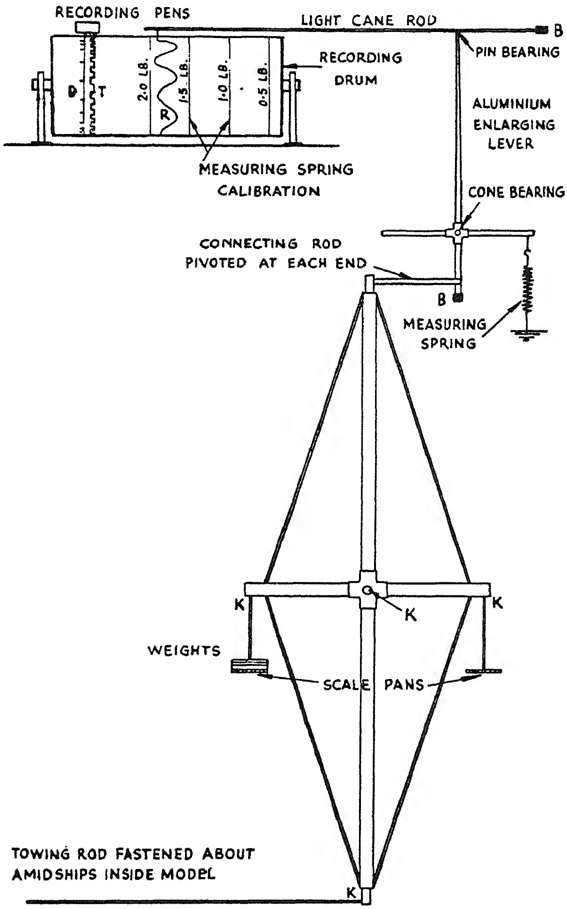

Fig. XXI. 3. Automatic recording dynamometer.

B. balance weight. K. knife edge bearing. D. distance record. Each jig represents 20 feet run. T. time record. Each jig represents 0.5 second. R. resistance record. Note that the total model resistance is given by the sum of the weights on the scale plan plus the mean value of the resistance record.

Propulsion Tests

A resistance test gives a guide as to the horse-power absorbed by the ship at a particular speed. The size of engine to be fitted to the ship obviously depends upon the efficiency with which the screw propeller can deliver this power.

To carry out propulsion tests a scale model of the proposed propeller is made and fitted to the model. Such model propellers are usually made of soft white metal and average 9 inches in diameter. A model rudder is also fitted, and in the case of twin screw ships, model bossings or "A" brackets have also to be made. Fig. XXI. 4 shows a model fitted up for propulsion tests and just about to be put into the tank.

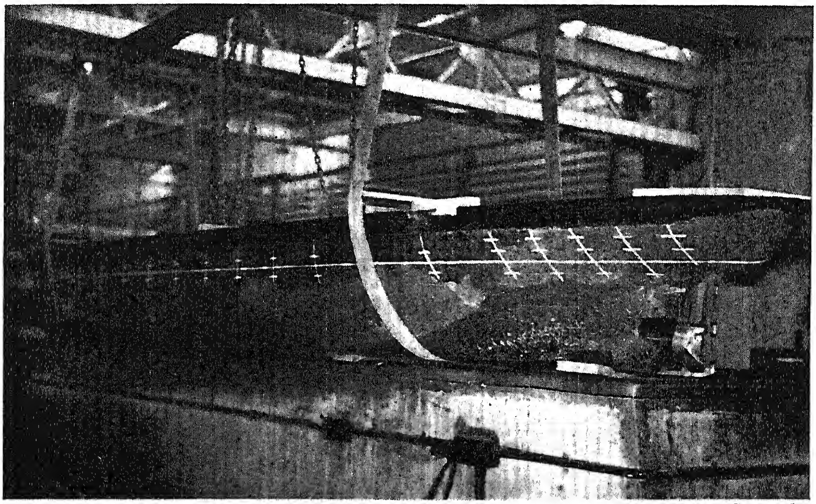

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Fig. XXI. 4. Model ready for propulsion tests.

The model screw is mounted on a shaft which is driven by an electric motor, and a recording thrustmeter, torsionmeter and revolutions counter are incorporated in the line of shafting. Fig. XXI. 5 shows this recording gear. The model hull is again attached to the carriage dynamometer. Propulsion experiments are carried out at one speed. As the model moves down the tank the screw is rotated and its revolutions, thrust and torque are recorded on the gear in the model. The carriage dynamometer now records the difference between the model resistance and screw thrust. Experiments are made over a range of screw revolutions and the results are plotted in the form shown in Fig. XXI. 6. From this chart a propulsive coefficient is obtained as follows :

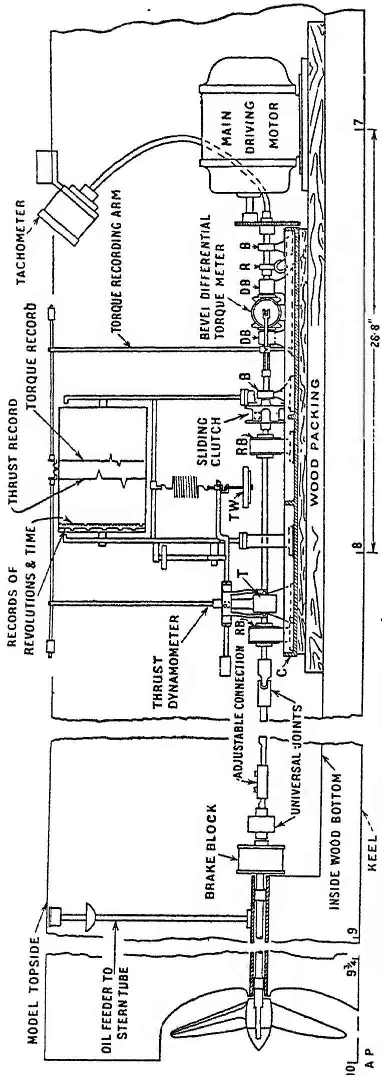

Fig. XXI. 5. Recording gear for propulsion experiments: B. single ballrace; C. cast iron base plate; D.B. double ball bearing; R.B. roller bearing; T. double ball bearing taking shaft thrust; T.W. thrust weight; R. revolution counter. The thrust dynamometer and the torque meter are calibrated twice during any set of experiments. Thrust is calibrated by putting a range of weights on the thrust weight scale pan, the recording pen marking the corresponding extension of the thrust spring. To calibrate the torque meter, the propeller is removed and a disc of equal weight fitted. The motor is then started and a series of known torques applied at the brake block and the corresponding torque meter readings noted. A torque calibration enables allowances to be made for the gear friction between the torque meter and the tail end shaft.

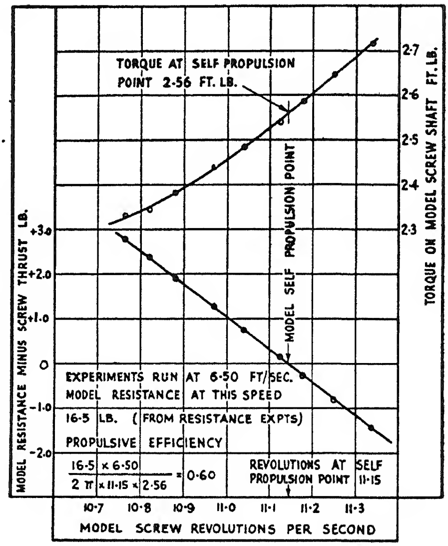

Fig. XXI. 6. Typical self-propulsion results for a model trawler.

$$\left.\begin{array}{l}\text{Efficiency of propulsion at self}\\ \text{propulsion point}\end{array}\right\} = \frac{Rv}{2\pi\, nq}$$

where R = model resistance in *lb.* at speed v ft./sec. from resistance experiments

v = speed at which propulsion experiments were made.

n = screw revolutions at model self-propulsion point per second.

q = corresponding torque measured on model screw shaft in foot pounds.

This, of course, is an ordinary efficiency formula obtained by dividing the useful work by the work put in. The propulsive efficiency so obtained is applied directly to the resistance test results. Thus if the resistance tests showed that a certain ship form at speed V ft.min. had a resistance of P pounds and the propulsive efficiency was found to be η, then these results would indicate that the vessel should be fitted with machinery capable of developing $\dfrac{PV}{33{,}000\ \eta}$ horse-power if the ship is to attain her designed speed.

Experiments are usually carried out in still water and it is customary, unless tests in waves have been carried out, to add 23% to the above shaft horse-power to make allowance for average weather at sea. This figure is based on research on actual ships during voyages to many parts of the world.

Special Facilities

Cavitation Tunnels. When a ship model propeller is tested in the tank, all conditions are to scale except the total pressure acting on the propeller surface. This is incorrect because while the water pressure head is to scale, the air pressure is 14.7 lb./sq. inch for both model and ship. This is an important omission since, under certain conditions, the ship propeller would exhibit cavitation whereas the model propeller would not. Cavitation may be described as a condition where the pressure over the propeller surface becomes so small that cavities containing air or water vapour are formed and there is an appreciable decrease in screw thrust. To study these phenomena, model propellers are sometimes tested in a cavitation tunnel. This is a large pipe, the ends of which are joined together to form a closed ring. Water may be pumped through this tunnel and, in addition, when the tunnel is not full, air may be exhausted from it. Thus, a model propeller positioned in the tunnel may be

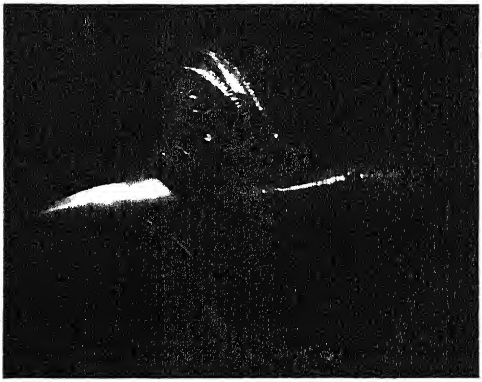

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Fig. XXI. 7. Cavitation on a model propeller.

made to operate under correct scale pressure conditions. Measuring gear is also provided and the variations in thrust and torque as the propeller revolutions are increased and as cavitation sets in may be studied. Fig. XXI. 7 shows a model propeller being subjected to cavitation experiments.

Circulating Water Channel. In an experiment tank a ship model is towed through the water and a limit is set by the length of the tank to the time which is available to take records. Some attempts have been made to reverse standard procedure and to devise a system whereby the water flowed past the model. The greatest difficulty has been to obtain a stream of water, the speed of which could be regulated to the necessary high degree of steadiness.

The Americans seriously attacked this problem, and in 1943 built a large circulating water channel. This has a test section 60 feet long and 22 feet wide, the depth of water being 9 feet. Water may be circulated through this channel at speeds up to about 17 feet per second. The test section is fitted with observation windows under water so that stream-flow over a model hull can be observed. No results of experiments in this channel have been published yet and it is thus difficult to assess the utility of this method of testing.

Steering Pond. The conduct of steering experiments is rather difficult in ordinary tanks due to their restricted widths. To overcome this difficulty large ponds have been built for such tests. The steering pond at Hamburg was about 330 feet diameter, the water being about 10 feet deep. Towards the end of World War II the Germans had begun an extensive series of steering tests on radio-controlled models. Full scale tests on captured German ships, particularly submarines, produced convincing evidence of their excellent manoeuvrability and this has been attributed to the many model steering experiments carried out by the Germans.

Other Ship Model Experiments

While many ships are modelled for resistance and propulsion tests only, on some occasions models are made for other test purposes. The stability of large warships has been examined using models made of sheet brass. Such models must be complete with watertight decks and bulkheads, they must be ballasted to a scale displacement and further, the positions of their centres of gravity and buoyancy must be to scale. Arrangements for flooding any of the large numbers of compartments must also be provided.

For a stability test, the model is floated in a glass walled tank and various schedules of flooding carried out. Observations are made of the stability under different damage conditions. A schedule can also be worked out showing the safest way to flood the ship in the event of a serious outbreak of fire in any of the main compartments.

Other experiments carried out on ship models have as their object the stress distribution in the ship structure under known conditions of loading. A model of the structure is made in xylonite; when polarised light is passed through such a model, it is split up into its colour components each of which corresponds to a known stress in xylonite. Such tests give only comparative stresses, but these are very acceptable since exact stress determination requires long and costly experiments on the full-size ship.

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CHAPTER XXII

AIRCRAFT MODELS AND WIND TUNNELS

The forces and pressures acting on an aircraft in flight cannot easily be calculated theoretically, and in most cases it is necessary to obtain the required information from measurements, either on the aircraft in flight or on a small scale model in a wind tunnel. There are considerable difficulties in making measurements of this kind in flight, because the attitudes and speeds of the aircraft are limited by the necessity for maintaining equilibrium and avoiding structural failure, and because it may not always be possible to carry all the necessary recording instruments in the aircraft. Moreover, the information may be required for an aircraft which has not yet been built. For these reasons, wind tunnels are extensively used for testing aircraft models and for measuring the forces and pressures acting on them.

A wind tunnel is essentially an apparatus for producing a steady stream of air. A model of an aircraft (or other body) is held in a fixed position in the air stream, and auxiliary apparatus is provided for measuring the air forces and for observing the flow.

Scale Effect

In predicting the behaviour of a full-size aircraft from measurements made on a small scale model, the important criterion is the Reynolds number R, given by

$$R = \frac{\rho v l}{\mu}$$

where ρ, v, and μ are the density, velocity, and viscosity of the air, and l is a representative length measured on the aircraft or model. (The Reynolds number is dimensionless, so that its value is the same whatever units are used for ρ, v, l, and μ, provided these are consistent.) If the Reynolds number can be made the same in the model test as in full scale flight, and if the air speed is fairly low in both cases so that the compressibility of the air does not have important effects, then the forces on the full-size aircraft can be predicted satisfactorily from measurements made on a geometrically similar small scale model. In most cases, however, it is not possible to make the Reynolds number the same in the model test as in full-scale flight, and it is then necessary to make corrections for "scale effect." The Reynolds number of the full-scale aircraft in flight is often about 10 or 20 times that of the model in the wind tunnel, but even with differences as large as this the scale effects on pressures normal to

the surface may be quite small. In the case of skin friction forces and drag, scale effects are usually much more important.

At air speeds above about 450 m.p.h., the effects of the compressibility of the air become important, and it is then necessary that the Mach number, defined as the ratio of the air speed to the speed of sound, should be the same in the model test as in full scale flight. For tests in which these effects are important, special high-speed wind tunnels are used.

Wind Tunnels

The simplest form of wind tunnel consists of a straight duct, open at each end, and provided with a fan near the outlet. The cross-sectional area of the duct decreases from the entry to the working section, where the model is mounted, then increases gradually towards the outlet. For most purposes, this type of tunnel has now been superseded by the closed return type, a typical example being shown in Fig. XXII. 1. In this type of tunnel the working section

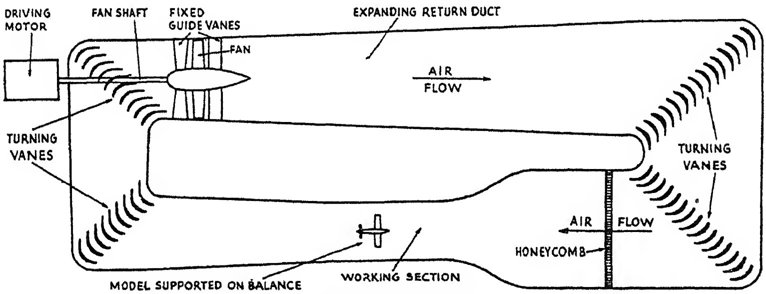

Fig. XXII. 1. Typical general purpose wind tunnel.

may be either closed, as shown, or it may be an open jet without any side walls. The closed type of working section is more usual in modern tunnels.

In a typical modern tunnel for general purposes (Fig. XXII. 1), the working section is about 13 ft. × 9 ft. and the maximum air speed is about 150 m.p.h. After the working section, where the model is held in position on a balance, there is a gradually expanding diffuser. The gradual expansion usually continues throughout the return duct until shortly before the start of the working section, where there is a fairly rapid contraction. A "honeycomb," consisting of a large number of thin hexagonal tubes, is often installed before the contraction to improve the flow. Turning vanes are provided at each of the four corners.

A number of special purpose wind tunnels have been designed for various types of work. One of the most important of these is the

high-pressure tunnel, in which compressed air is circulated in the tunnel, at a pressure up to about 20 atmospheres. The object of this is to increase the Reynolds number by increasing the density of the air (viscosity is almost independent of pressure). For example, a test on a 1/10th scale model at a pressure of 10 atmospheres would give the same Reynolds number as the full scale aircraft flying at a speed equal to the air speed in the wind tunnel.

Other tunnels have been designed to give very high air speeds, for tests in which the compressibility of the air is important. In these tunnels, speeds up to about four times the speed of sound have been reached. (The speed of sound in air depends only on the temperature, and is about 740 m.p.h. at 0° C.)

Model Construction

For tests in the ordinary type of wind tunnel, at atmospheric pressure and at speeds not exceeding about 200 m.p.h., wooden models are normally used. For higher speeds or pressures, metal models are usually necessary. The models are made as accurately as possible, with a smooth surface finish. In most cases, no attempt is made to reproduce small aircraft details, such as exhaust pipes and radio aerials, because there is a large "scale effect" on these small parts, so that the results of model tests may be misleading if they are represented. If necessary, the effects of small excrescences may be investigated on a larger scale model, representing only part of the aircraft.

In tests on aircraft models it is usually necessary to represent correctly the flow of cooling air through radiators or over air cooled engines, although for the reasons explained above the actual engine details are not represented on the model. The ducts for the cooling air are reproduced on the model, and the correct flow is obtained by inserting baffle plates to give the required pressure drop.

For investigating the effects of propeller slipstream, tests on aircraft models with propellers are sometimes made. The propellers are driven by small electric motors, of extremely high power for their size, buried inside the model.

Measurement of Force

For measuring the forces and moments acting on a model in a wind tunnel, balances are used. Most of these depend on the simple weigh-beam principle, and they may be classified according to the method of supporting the model. In a "roof balance" (Fig. XXII. 2), the balance is mounted above the working section of the tunnel, and the model is suspended from it in an inverted position, usually by means of wires. The other type of balance is installed underneath the working section, and the model is mounted on it, right way up, by means of struts. The roof type of balance is more often

used in ordinary low speed tunnels, and Fig. XXII. 2 shows the principle of operation of a simple balance of this type. The lift on the model is measured as a downward load at two points, thus giving the magnitude of the total lift force and its line of action (or the

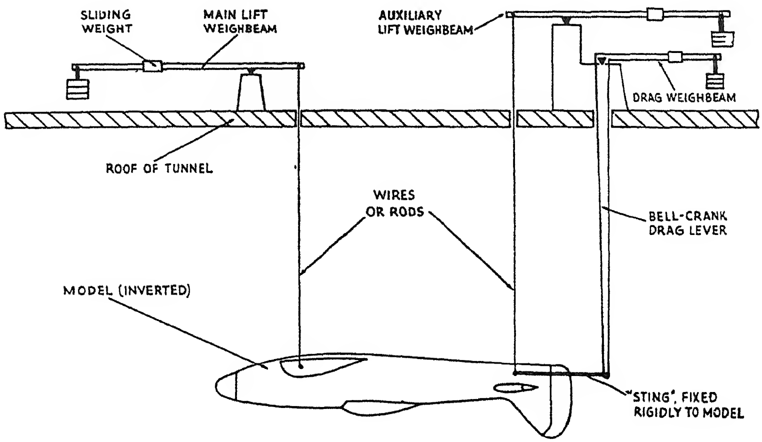

Fig. XXII. 2. Principle of operation of wind tunnel balance.

lift and pitching moment). The drag force is measured by means of the bell-crank lever and weigh-beam shown at the rear of the model.

The balance shown in Fig. XXII. 2 measures only lift, drag, and pitching moment. These are the quantities most often required in wind tunnel tests on aircraft models, but for investigations of lateral and directional stability it is also necessary to measure the rolling and yawing moments with the model yawed. The side force is also required for some purposes. Many wind tunnel balances are made to measure all three forces and three moments, with provision for varying the angles of incidence and sideslip over a wide range.

In practice, wind tunnel balances are often much more complicated than the simple arrangement shown, even when the only quantities required are lift, drag, and pitching moment. Refinements are added to reduce the interference effect of one force component on another and to increase the accuracy and speed of working. In a good modern balance the error in the measurement of a force, as given by a static loading test, is usually not more than about $\frac{1}{10,000}$ of the maximum force which can be measured. This high accuracy is not required when the force to be measured is large, but it is very desirable when the total force is small, i.e. when the wind speed is low.

Measurement of Air Speed and Pressure

For the measurement of air speed in a wind tunnel, pitot and static tubes are used (Fig. XXII. 3). When the pitot tube is mounted with its open end facing upstream, the air in the mouth of the tube is brought to rest, and the pressure recorded is known as the total (or stagnation) pressure. In the static tube the end is closed, and several small holes are drilled in the tube at a considerable distance (8 or 10 diameters) from the closed end. The pressure recorded at these small holes is that of the undisturbed air stream, and is known as the static pressure.

From measurements of the total and static pressures, the air speed can be determined, using the equation

$$\text{(Total pressure)}-\text{(Static pressure)}=\tfrac{1}{2}\rho v^2\left[1+\tfrac{1}{4}\left(\frac{v}{a}\right)^2+\tfrac{1}{40}\left(\frac{v}{a}\right)^4+\ldots\right]$$

where v is the air speed, ρ is the density, and a is the speed of sound. For low air speeds, the terms in $\left(\frac{v}{a}\right)$ are negligible, and the difference between the total and static pressures is simply equal to $\frac{1}{2}\rho v^2$.

For convenience, the pitot and static tubes are often combined, the static tube being in the form of an annulus surrounding the pitot tube (Fig. XXII. 3). The difference between the total and static pressures, giving the air speed, can then be observed directly.

For measuring the direction of the air flow past a model, the yawmeter shown in Fig. XXII. 3 is used. If the flow is parallel to the

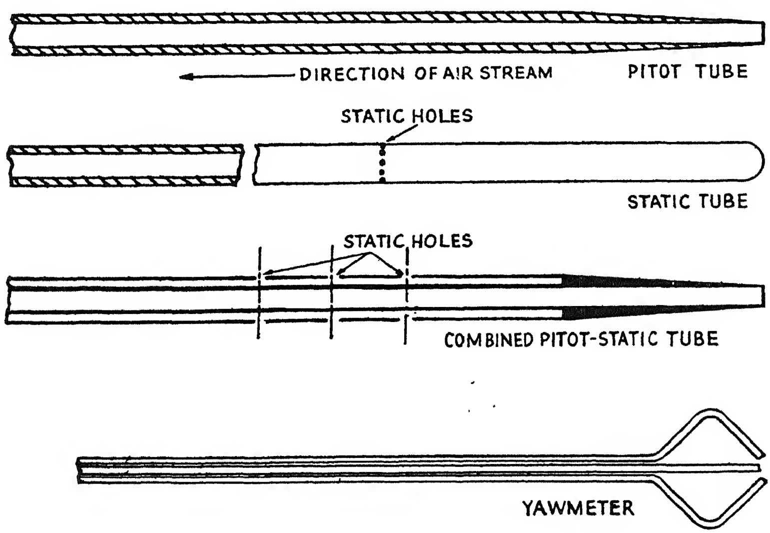

Fig. XXII. 3. Pitot and static tubes and yawmeter.

axis of the instrument the two inclined tubes record equal pressures, but if the flow is inclined the recorded pressures are no longer equal. The direction of the stream can be found by adjusting the inclination of the instrument until the pressures recorded by the inclined tubes are equal. Alternatively, the instrument can be calibrated, so that the direction of the flow is known for all values of the observed pressure difference given by the inclined tubes. In some yawmeters, there are four inclined tubes, instead of two as shown, so that the inclination of the stream can be determined in two perpendicular planes. The central tube shown in the yawmeter is an ordinary pitot tube, used to record the total pressure.

For measurements of the pressure distribution on the surface of a model, the most satisfactory method is to build a special model with flush fitting surface holes. Each hole is connected to a manometer by means of tubing passing through the inside of the model. Alternatively, a small movable static tube can be used to explore the pressure distribution on the surface of the model. This method is less accurate but it does not require the construction of a special model and alterations to the model can be made more easily.

The pitot and static tubes described above are usually connected to simple U-tube manometers for the measurement of pressures. For low air speeds, where the pressures to be measured may be only a few millimetres of water, the Chattock tilting manometer is used (Fig. XXII. 4). This instrument consists of two reservoirs of water, with a connecting tube between them. A third vessel, in the middle of the connecting tube, is made in two parts. The inner part is a tube which is completely filled with water, and the outer part is a larger diameter tube which has water in the lower half and medicinal paraffin completely filling the upper half. This arrangement gives a surface of separation, in the form of a "bubble," between the water and the paraffin, which can be observed with a microscope and used to detect any small flow between the two main water vessels. (To avoid confusion, the microscope is not shown in the diagram.) In use, the instrument is tilted to bring the "bubble" back to the zero position, and the angle of tilt is given by the reading of the micrometer. The pressure difference can be calculated from

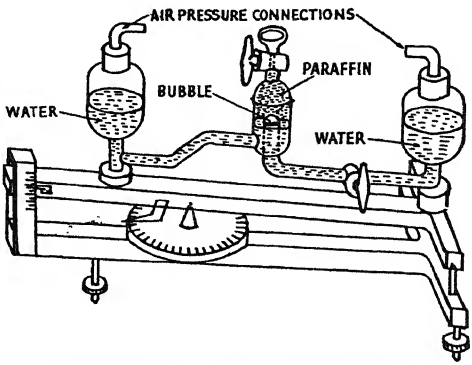

Fig. XXII. 4. Chattock manometer.

the angle of tilt and the dimensions of the instrument, without any calibration. A sensitivity of 0.0001 inch of water pressure difference is easily obtainable.

For measurements of fluctuating velocities (e.g. in turbulent flow), and for measurements of very low air speeds, the hot wire anemometer is often used. In this instrument, a fine platinum wire is supported in the air stream and heated electrically to a temperature of about 200° C. The rate of cooling depends on the air speed, and hence the speed can be determined by finding the heating current required to maintain a given wire temperature (i.e. a given resistance).

Visual Methods

A number of visual methods have been developed for investigating the flow of air past a model. Perhaps the simplest of these is the use of threads of silk or wool, either fixed to the surface of the model or supported on a wire. These threads indicate the direction of the flow, and also show the presence of severe turbulence by their unsteadiness. Smoke has also been used for making air flow visible, but it is only possible to use this method at low air speeds. If the smoke is introduced through several small orifices, the filament of smoke issuing from each orifice can be seen, and the direction of flow at any point is given by the inclination of the smoke filament. At any point where there is severe turbulence in the air the smoke filament becomes diffused and thickened.

Most of the other visual methods depend on changes of air density, and thus they are normally only used at high air speeds, because at low speeds only very small changes of density are produced in the flow of air past a model.

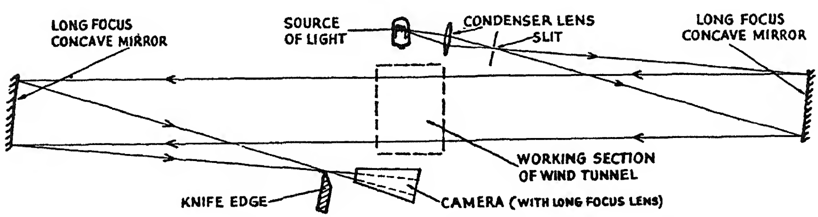

Fig. XXII. 5. Optical apparatus for "schlieren" photography.

Fig. XXII. 5 shows the optical apparatus used in "schlieren" photography. Light from any convenient source is focused on a slit, which is placed at the focus of a concave mirror. This gives a parallel beam of light, which passes through the glass walls of the wind tunnel, and is brought to a focus on a knife edge by a second concave mirror. Any transverse density gradients in the wind tunnel give corresponding gradients of refractive index, and thus deflect the beam of light

either towards the knife edge or away from it. The amount of light entering the camera depends on the position of the beam relative to the knife edge, the illumination being reduced as the beam is deflected towards the knife edge. Thus any change of density gradient in the air causes a corresponding change of illumination on the plate.

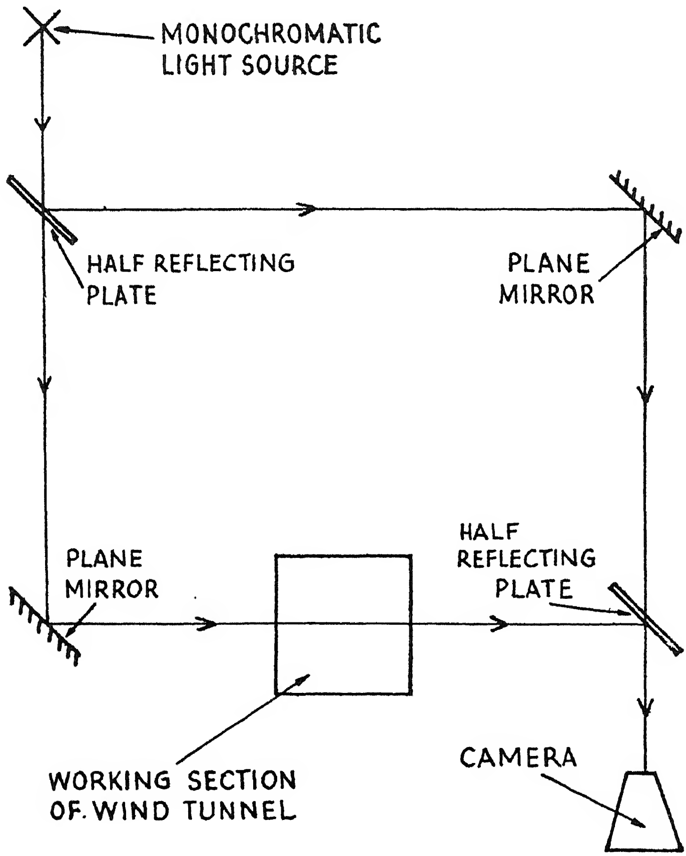

Fig. XXII. 6. Principle of the Mach-Zehnder interferometer.

Another instrument which has been used for observing changes of density in air is the interferometer and the type which has been most used for wind tunnel work is the Mach-Zehnder interferometer, shown in Fig. XXII. 6. Light from a monochromatic source is separated into two beams by a half reflecting plate. One beam passes through the wind tunnel, while the other does not. The two

beams are finally re-combined, and may be made to produce interference fringes. Any change of air density in the wind tunnel causes a change of optical path for one beam, and hence displaces the fringes. From the resulting fringe pattern, the density at each point in the field can be calculated, and hence, by making some assumptions, the pressures and speeds can be calculated. Unlike the "schlieren" method, which is usually only a qualitative one, the interferometer gives quantitative results.

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CHAPTER XXIII

STRATEGICAL COMPUTING MACHINES

The calculating machines familiar to scientific workers are specialized devices with cast-iron habits. Once fed with the data they carry out one of the four rules of arithmetic more or less automatically, but the initiative, and the input, output, and ordering of the data and operations demand a human operator. Even where the storage of intermediate results, their transfer and recording can take place within the machine, the decision which of these functions should operate and when, and the overall course of computation, demand human supervision.

For some computations at least the strategy is essentially mechanical. The operations to be performed have a fixed order, whatever the results generated throughout the course of the calculation. If the machine or group of machines can be fitted with some administrative controls, pre-set to the required order of operations, the computation can be carried out without further attention. Moreover, if the pre-set order can itself be materialized in some form directly intelligible to the machine (cams, punched cards, perforated tape, magnetised wire, etc.), this can be filed, and no further intellectual effort will be required for any job calling for this strategy, or "Programme," as it is usually called.

Early Calculating Machines

Machines of this kind, of various levels of complexity, are fairly common. Typical are the accounting machines, in which complex patterns of cumulative additions and subtractions can proceed automatically (and therefore much of the numerical applications of the calculus of finite differences). The general principles of a more universal machine were established by Charles Babbage a century ago, and a small part built before his death in 1871. If completed, this "Analytical Engine" would have had the essential features of contemporary and forthcoming strategical computors, so far as a purely mechanical device could incorporate them. There was a "store" in which numbers were represented, as in ordinary desk machines, by the configurations of sets of toothed wheels ; a "mill" which could add, subtract, multiply or divide any two numbers supplied from the store ; and a Jacquard apparatus controlling the mill and store, itself controlled by pre-punched cards. The output could be transferred to store or printed automatically. For any unit process in the computation there were four cards ; the first set the mill to

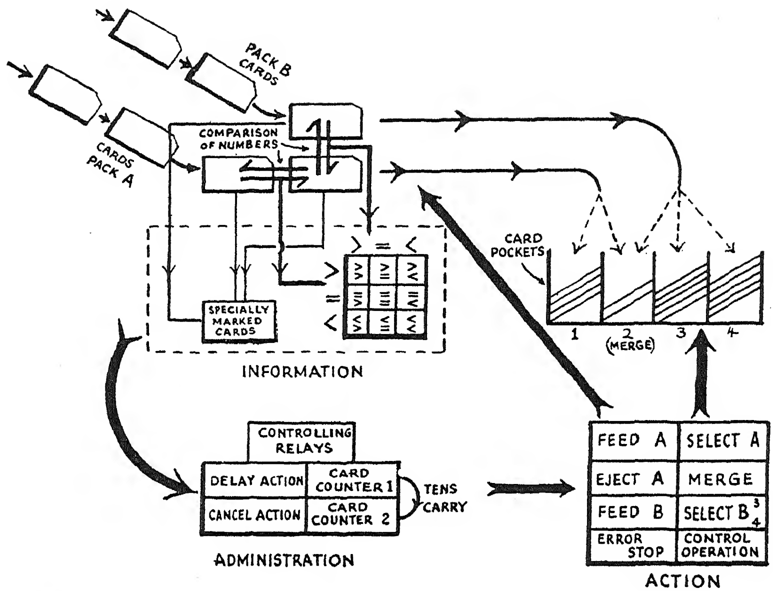

Fig. XXIII. 1. Automatic Administration. Scheme of a punched-card Collator, which files, orders, and separates packs of punched cards according to pre-set instructions. The numbers on the leading cards of the two packs are compared, and those on the leading and next following card of pack A. The nine possible combinations of 'greater than', 'equal to', or 'less than' cause electrical impulses to close relays in the Administration section which are connected to operate delaying, cancelling, or counting circuits. These in turn operate the feeding and destination of the cards into the pockets 1, 2, 3, 4. Both packs can merge in pocket 2 ; cards from pack A preceding those from pack B. By suitable pre-set switching of the relays, the collator can remove in order all cards with numbers between given values ; match cards from one pack with corresponding cards from the other ; check sequences ; replace cards in their proper positions ; and all other operations that would require a filing clerk. The controls of strategical computing machines work like this, but from more complex information, under fuller administration, and with wider actions.

the required operation, the second and third located the operator and the operand in the store, the fourth gave the destination of the result in the store. The apparatus was not self-conscious. That is, it could not compare results standing in the store at any stage; making difficult any computation using tactics depending on results as they are obtained (e.g. "repeat instructions until the first n digits of two consecutive results agree").

Enough of the Analytical Engine was built to show that, given unlimited backing, it could have been finished and worked, using the techniques then available. The theory, the mechanical design, and even the construction of the prototype units were the work of one man, a man moreover distinguished as a pioneer of modern

logical analysis, the father of scientific management, and in other fields also. Twenty years after his death it inspired much of the first Hollerith machines built for the U.S. Census of 1890, and fifty years later still, the I.B.M. Automatic Sequence Controlled Calculator at Harvard, which is, in fact, the Analytical Engine with all the benefits derived from advances in high-speed electro-mechanical relays.

Purely mechanical design for apparatus of such complexity causes grave difficulties, largely in the geography of the components, most of which have to be inter-coupled with each other. Something of this can be guessed on seeing the interlocks within an ordinary automatic desk machine or, on a larger scale, the interlock frames of a signal box at some railway junction. At some level of complexity, unless the apparatus is to smother itself, electro-mechanical or purely electrical components must be brought in.

The Analysis of Computation

Clearly, instruments of the kind described can deal with a large and important part of computation. To what extent can they, quite apart from practical difficulties, deal with any computation ? Can, in theory, a machine be built to compute any special number, and, if so, can a single universal machine be built that can carry out all the specialities of the separate machines ?

For these questions to become meaningful, "computation" and other words would have to be defined with great precision. But, in the sense that the questions are likely to be asked by physicists, engineers, statisticians, sociologists and administrators, the answers are all *yes*. This is at least plausible for, from the nature of mathematics, if a numerical answer is possible at all, it should be independent of the age, sex, race, state of conscience and political opinions of the computor, so long as correct instructions are carried out correctly. So long, in fact, as the computor behaves like a machine.

True, human qualities such as "flair," "intuition," "experience," still serve to shorten ordinary computations, but these are only dignified names for unsystematised knowledge, and the speed of existing pioneer machines is so high that any shortening obtained by flair would not be worth the initial work. The aim of current designs is to achieve any arithmetical operation (e.g. the multiplication of two twelve decimal–digit factors) in not more than forty micro-seconds ; that is, 25,000 arithmetical operations a second. Intellectual effort would be better expended at some other level.

The answers to the questions in the first paragraph of this section and, what is quite as important, the logical specification of a Universal Computing Machine, were given by A. M. Turing in a paper to the *London Mathematical Society* in 1936. As the argument and conclusions can be expressed with precision only in the language of

symbolic logic, a crude and picturesque sketch is all that can be given here. Imagine first a specialist machine; for example, one to calculate the roots of a given type of equation. At any stage it would have within it certain numerical data and certain instructions (in practice, coded in numerical form also). From these it would form automatically, by the inner logic of its construction, new data and instructions, and so on, until the results were achieved and the instruction "stop" generated. If it ever repeated the same data and instruction it would, of course, continue the cycle indefinitely, but this difficulty must be ignored here.

The logical specification of this special machine can be expressed exactly and uniquely as a number and any machine for any special purpose will be exactly described, as to its logical design, by one number and one number only. Imagine now a machine that, when fed with one of these "description numbers" sets its internal connections to correspond. That is, it temporarily becomes that special machine. If the description number is followed by the initial data and instructions, it will then compute the number required as if it were the special one-purpose machine, until another description number comes along and it resets itself as another specialist machine. Such a machine would be a true universal calculating machine.

The Universal Calculating Machine is "biological" rather than "mechanical" in its basic design. Instead of being built up, like most instruments, from extremely specialized components, performing complex functions with great skill, the Universal Machine is built of extremely simple unspecialized "cells". These are mobilized into special organs when required, and demobilized and remobilized as other requirements arise. From this point of view, existing calculating machines are universal machines with "permanent reflexes"; groups of organs so bound together that they can act in one way only, and cannot be redistributed for other functions. In contemporary practice special organs may be convenient and simpler; e.g., the I.B.M. Automatic Sequence Controlled Calculator has not only special organs for addition and multiplication, but also for forming logarithms and trigonometric functions, and division with a variable divisor (used, for instance, in extracting square roots). Nevertheless, the path to universality does not lie, as would be expected, in the inter-coupling of more and more organs performing more and more complicated arithmetical operations, but in having less and less of them with more flexible administration.

One consequence of this concept is that, even at the present day, the wider and more powerful the scope of a strategic computing machine, the less physically complex does it become. In the author's personal opinion, even a very specialized machine is best designed on universal lines, the administration rather than the components being then specialized. It is more economical to have a device built

of "on-off" units than one built of "0, 1, 2 . . . 9" units. Actually with r decimal positions we can represent all numbers less than 10^r. Or, put the other way round, to represent a number N in scale of ten, we need $[log_{10} (N + 1)]$ decimal positions (taking the next whole number upwards). In each decimal position there must be means for indicating nine possible elements or operations corresponding to the digits 1 to 9, 0 now being represented by "no-action". Similarly, in scale of two, we need $[log_2 (N + 1)]$ digital positions, but only one operation or element, representing the single digit, 1. So the ratio of elements needed to represent a given number in a decimal, to that in binary instrument is $9\ log_{10} (N + 1) \div log_2 (N + 1)$ or $9/log_2 10$, which is 2·7 roughly. The number of digits needed in a scale-of-s instrument is, by the same reasoning $(s\text{-}1)\ [log_s (N + 1)]$. This is a minimum when s equals 2, so binary instruments are more economical in elements than those using any other scale of notation.

The fundamental reason for this very marked difference between calculating machines and other scientific instruments is that, unlike thermostats, photographic lenses, cyclotrons, centrifuges and all the rest, calculating machines *do not have to perform any physical function* except of course incidentally, such as recording results in physical form. A calculating machine must be able to take up a number of clearly labelled stable states according to formal rules, not according to physical conditions as in other instruments. It is not surprising, therefore, that the design of calculating machines involves the techniques of symbolic logic—of which it is an almost pure example—but does not involve mathematical physics. Its realization as a working instrument involves, however, every available aid of physics, particularly developments in high frequency devices, such as are called for in television, radar, sound recording and high-speed photography.

The Switchboard Analogue to Logic

All arithmetical operations, however complicated, boil down to a list of situations in which something is done, or is not done. There is no third course. For instance, in addition in the decimal system, tens-carrying takes place according to the sum of the digits exceeding or not the total of nine, and the presence or absence of a carry-in from the right. All possibilities can be listed, and the action of the tens-carry given as "yes" or "no" under each of them. The tens-carry can be considered as a switch, mechanical or electrical, and its "yes-or-no" response designated by the digits 1 or 0. Similarly, the states of the addends and the carry-in can be designated by groups of digits 1 or 0. Our list then becomes a list of numbers (binary numbers) followed by single numbers, 1 or 0, representing the state of the tens-carry switch. It is now necessary to build a switch or relay network whose possible states agree with this numbered list,

the 0's and 1's having the same meaning of Off or On. The network would then be an addition network of the kind required. Actually so simple a network as this, and others far more complicated, would be done by experience and are so done on the plug-boards of punched card machines. It is important to realize that, in fact, the network can be arrived at purely automatically by the application of a peculiar algebra, Boolean Algebra, that is so simple as to be very puzzling at first sight. It will be found in any text on Modern Algebras. Its interest here is that it is directly intelligible in terms of relays. Consider the condition "A and B"; that is, the properties "A" and "B" simultaneously. This is represented exactly by two relays in *series*, energised by condition A and condition B severally. No current can pass unless both relays are on, which is as required. Similarly the condition "A or B" (i.e. "either A, or B, or both") is represented by the two relays in *parallel*. Use of back and front contacts on the relays allows similar handling of the negations, "not-A," "not-B," etc. One can see, for instance, the equivalence of "A and B" to "not-(not-A or not-B)", and express it as a relay system. Thus any consistent complicated association of properties calling for Yes or No responses can be represented exactly, and automatically, by an assembly of relays coupled in series or parallel.

In particular, all arithmetical requirements, once scheduled, can be achieved by the appropriate connections of simple on-off relays. These connections can be either permanent or controlled by some switching control at a higher level of control or automatic administration.

The state of the relays at any stage can be represented by, or itself represent, a binary number. This, using the digits 0 and 1 only, can be conveniently stored or transmitted as a series of pulses or absences of pulses and can suffer a good deal of distortion without ambiguity.

It should be said that Boolean Algebra itself, apart from the switch analogy, is of practical application. In some U.S.A. Insurance Offices, it is used to check complicated clauses in insurance policies. Its value in checking complicated verbal statements should in fact be applied far more widely, and this work could be done on a Universal Calculating Machine just as readily as any more conventional arithmetical problem.

Numerical Coding of Instructions

By now it will have been seen that numbers within a strategical computor may signify more than numerical quantities. They may signify, in whole or part, connections of the machine, instructions for operations, or merely descriptive labels, "addresses" as it were to which sets of pulses should be sent. For this reason such numbers are called "Words" in current practice. The standard word is a

pulse train 40 units long, corresponding to a 12 or 13 decimal digit number. A unit is about one micro-second long on electronic computors.

Coding obviously should not be arbitrary. As a systematic technique, it is a relatively new topic, and as usual is based on logical considerations. The following example, rather trivial, taken from ordinary punched-card computing, may illustrate the type of problem.

Numerical quantities must bear a symbol indicating their sign and whether they are real or imaginary. Products of these quantities must do so also, and the symbols must be generated automatically. One way of doing this is to have a two digit code. In the units place is a 0 or 5, according as the number is real or imaginary. In the tens place is an even or an odd digit, according as the number is positive or negative. When numbers are multiplied, their codes are added and the tens and units of the sum punched automatically along with the product. This new code number will be correct, as a test will show. In much the same way on a universal machine, where a different strategy is called for according to the result achieved (as in a "trial-and-error" procedure) the system can be arranged to add to the current instruction code number a number depending on the result just achieved so as to produce the instruction number appropriate to the new situation.

The Relay Elements

The relay or switch elements can be anything from mechanical locks to electronic valves. Minute coherers, a relic of pioneer radio work, might be used ; while the elements on television image-storing tubes certainly will be. The last are not in themselves relays, but in association with the scanning beam and amplifiers can act as such. The fundamental need is for small, cheap, switch-like components that do not need much individual installation. This is because of the very large numbers needed. On any machine that is to have reasonable scope about half a million binary digits, 0 or 1, have to be handled or stored. If these were all represented by the on or off condition of relays, the cost and labour would be colossal. Actually, as we shall see, static representation is not necessary, but something around 15,000 relay elements seem to be required apart from any question of storage. The installation of a mass produced automatic telephone relay, say, costs anything from £5 to £15.

The use of more complicated relays, like the telephone relay above, which is bi-quinary (one contact to represent +0 or +5, and five others representing 0, 1, 2, 3, 4) comes from the enormous quantities that are mass-produced for other purposes. Ultimately they are not likely to be used, although the current Bell Telephone Computors are very successful with them. Being mechanical, they cannot have the speeds that will be universally demanded, they

compel too much storage on punched cards or tape, and force the machine to use the decimal system internally. On a pure on-off relay machine decimal working can be produced whenever wanted by ganging the relays in sets of four, and instructing them to reset when reaching the pattern (input on the left) off-on-off-on. And similarly for working in duodecimals, sterling, or anything else. The results can be produced in any form. What form is used within the machine is the machine's worry.

The basic electronic on-off relay is the familiar "flip-flop" or trigger; a pair of triodes so connected that one and only one is conducting at any time. Pentodes and other multi-grid tubes are used as elements of higher administrative grade.

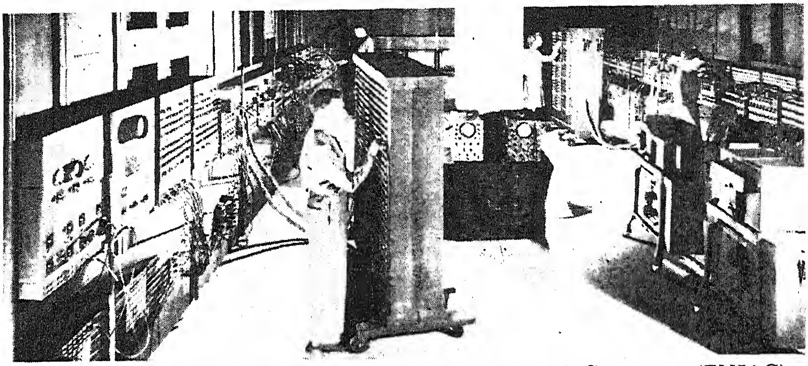

Fig. XXIII. 2. Electronic Numerical Integrator and Computor (ENIAC), University of Pennsylvania.
The control and initiating unit is on the left, the final results coming from the printing units to the punched card reproducers on the right. Round the floor are the trays containing nine trunk cables of eleven wires each, and ninety-nine 'programming' trunks of one wire each. The various units (multiplier, square-rooter, etc.) on the walls are connected at will to these trunks. The portable switchboards are function tables upon which arbitrary functions are being set by hand.

Very high-frequency relays reduce the numbers required considerably. For, given some form of storage, the relay can undertake successively what would otherwise be done by several relays simultaneously. For instance, given recording and storage, and a high enough speed, an ordinary pin-wheel machine could operate on only one "slice" of the usual mechanism.

The practical consequence of the different kinds of relay is mainly one of speed. A ten digit by ten digit multiplication, including recording the result, would take a human operator with a first-class mechanical, electrically-driven calculating machine, about half a minute. An electro-mechanical machine would take about three seconds; an electronic machine, something between 3,000 and 50 *micro*-seconds, the last being something of a target value.

These times take no account of the "overheads" arising in a complete computation ; say the evaluation of a family of differential equations. Here time needed for input, scanning of data stored in memory-registers, comparison of results, and output in recorded form, etc., predominate. Roughly speaking, an electro-mechanical machine is 100 times faster than a humanly-operated mechanical machine, and electronic machines can be from 60 to 1,500 times faster than electro-mechanical. Moreover, the automatic machines can and do work a 24-hour day.

Storage and Memory as Delay

So that the single relay can successively take the place of several relays, some kind of delay must be given to the results of its actions, so that it can accept these as the input for its next activity. The same concept of delay as a substitute for static storage in relay banks, tape, packs of punched cards, etc., is general in all modern machines. The static devices have their value ; punched cards give an unlimited memory, and the data can be recorded and classified as desired. To use any device needing mechanical handling for the internal memory of the machine is, however, impracticable. At the speeds contemplated the consumption of power alone would be colossal. The storage is carried out by delaying the "words," which are in the form of electro-magnetic waves, electrostatic charges, compression waves, or other non-material processes.

Various lines are being attacked. Slow electro-magnetic waves produced by wave-guides, continuous delay lines, or artificial transmission lines have been proposed. The image-storing devices used in television, which has identical problems, are obvious as practical "word-storers". Special tubes, suggested by television techniques, are being designed.

A device inspired by television is the mercury delay line. This is practical and convenient. It is a tube of mercury, about two and a half inches long, with a crystal oscillator at each end. The pulses forming the word oscillate one crystal and send a corresponding train of compression waves down the mercury. These oscillate the other crystal when they reach that end, and generate a signal that, after amplification, is returned to the original end. The word thus circulates till called for. Acoustic impedance is considerable, and about 500 : 1 amplification is necessary. Even allowing for the simple "pulse or no-pulse" nature of the word, distortion has to be dealt with. By various ingenuities the word can be allowed to circulate indefinitely without becoming unintelligible or ambiguous.

All storage devices, including those of desk machines, must be able both to "read out and clear" and to "read out and retain storage". These operations are usually called, not too intelligibly, "Total" and

"Sub-Total" ; terms arising from accountancy. The author's terms, for local use, may be of wider application. They are "Transmit" and "Report" respectively.

Input and Output

The machine has to have communication with human beings before and after its operation. The input of data can be through punched cards or tape and, for constants and arbitrary data used in the course of calculation, by manual setting of switches on a relay bank. All methods are commonly used on the same machine. Instructions are generally on tape of some kind, though permanent instructions and data are plugged on switchboards, as with current punched-card machines. The instruction tape is automatically advanced and scanned for appropriate guidance according to codes produced within the machine, as indicated above.

Output is more difficult. To produce a written record some mechanical process is needed, though experiments with photographic recording of cathode ray displays are going on. Nevertheless, a reasonably printed result will be needed at some stage, and there is little point in throwing away the value of the machine by using the relatively enormously slower human methods of presenting printed results, together with the inevitable errors that come in. So far, output is generally on to punched cards, by way of a storage

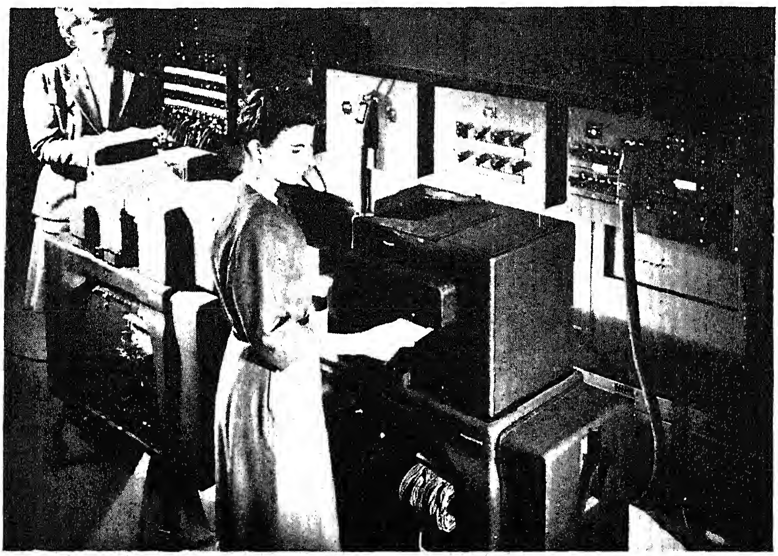

Fig. XXIII. 3. Output Units of ENIAC. The results are being delivered in the form of punched cards by commercial punched-card reproducers plugged into the printing unit of the ENIAC proper.

device that holds the results till required. Automatic typewriters and telegraph tape are also coupled, and there is no reason why composing machine tape should not be prepared automatically at the same time. Punched cards working a variable type, variable space electrical typewriter have produced directly some very seemly results, notably the U.S. Air Almanac. Moreover, proof-reading in the ordinary sense has been eliminated, being replaced by a process of comparing packs of punched cards. This can be done automatically at high speed on commercial punched-card apparatus.

Checking and Maintenance

In an instrument made up of thousands of elements, some elements or their connections must fail over a given period of time—a short time if they work at very high rates. Faults must at least stop the machine or better, to avoid loss of machine time, must bring in alternative circuits or even an alternative calculation. Signals are therefore sent to the controls after each operation and, unless these confirm the instructions, the machine cannot go on. The signals must be constructed to locate, as well as indicate, a fault. This is not easy, because various combinations of faults may give rise to the same signals, even to the signal indicating correct operation. Such possibilities and the probabilities of different patterns of failure are derived from statistical analysis of tests. No instrument can be completely self-checking, any more than it can be completely self-repairing. For the 'checking unit' must contain, as a guide to its operation, an image in some form of the structure of the instrument. This must contain an image of itself, because it is a part of the instrument—and so on. So at some level checking must be done by human intelligence and knowledge devising alternative methods carried out on different machines or different parts of the same machine.

Conclusion

No attempt has been made here to give detailed descriptions of existing machines. These can be read in the current press, or in the articles listed in the bibliography. The subject is developing so rapidly that many of these machines are modified profoundly before the articles are published. What has been attempted is to present in ordinary language the principles upon which these machines must be based, whatever the technical nature of their components.

Some puzzlement may be felt as to the purpose of so apparently fantastic a kind of activity. Existing machines were built mainly because of the urgent demands of war ; the need for ballistic tables in particular. The need is actually deeper. Modern science and government are deeply concerned with information that can be obtained either from the analysis of vast quantities of data, sometimes

a very involved analysis, or from large and costly experiments. Moreover, the results are needed at once to be of any use. Examples of this can be seen in nuclear physics, meteorology, structural engineering, economics, communication engineering, and sociology. Even if time were not important, the clerical staff is not there. The great French trigonometrical tables were made by using as computors the hairdressers left unemployed when wigs became unfashionable. No such solution is likely to help us. Many scientific and other organizations are too much like English country houses, beautifully designed on the assumption that there is an unlimited supply of cheap domestic labour. It was not chance that the first big computing machines were made to deal with the Census, and that calculating machines were made necessary by commercial, not scientific, necessity.

This necessity now applies to the scientific field and, one hopes, this country will again take the lead it gained, and forgot, in laying the foundations of the Analytical Engine.

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CHAPTER XXIV

CONSIDERATIONS IN THE DESIGN AND MANUFACTURE OF INSTRUMENTS

Instruments for the measurement of physical quantities, whether for use in the laboratory or factory, are generally based on either one of two broad principles. One is the method of balance or coincidence, as typified by the chemical balance, the navigator's sextant, and "null" electrical methods in general ; the condition of balance being detected automatically, or by the operator's eye, although other senses can sometimes be brought into play. The other is the deflectional method in which a pointer or index is caused to move by the unknown quantity to an extent proportional to its value. The fundamental difference between these two can be shown by simple examples. A mass can be weighed by a chemical balance or a spring balance. The first employs the principle of coincidence, for weights are placed on one pan until they are equal to the mass on the other. When it is placed on a spring balance it causes a pointer to move over a scale on which the weight can be read as a result of a previous calibration. Similarly, when an electric current is measured by means of a shunt and potentiometer, a balance or "null" method is being used, whilst an ammeter, which does the same job much more quickly, but possibly not so precisely, uses the deflectional principle. In fact this example shows the principal differences between the two methods, for although most quantities can be measured either way, the first is often the more accurate, whilst the second tends to be more rapid and demands less complicated apparatus.

But accuracy is a relative term, and though often the most important quality of an instrument, may on some occasions not be so essential as others such as robustness, ease of use, rapidity of response, freedom from maintenance, cheapness and durability. Therefore, since the greatest precision usually demands some sacrifice of these other virtues, it is wise, when possible, to select an instrument having accuracy suitable for its purpose. This may be a difficult task when the best accuracy is demanded, for the ultimate performance of an instrument depends on many factors, each having to be recognized and studied separately.

Sources of Errors

It is worth noting in the first analysis that the performance of a balance method depends mainly on the sensitivity of the means for detecting an out-of-balance condition, and on the stability of the

reference quantity, and the accuracy of a deflectional method on the constancy of the force opposing the deflection, and errors in the means of producing the deflection. Both types are liable to errors of two distinct classes. One class originates in those changes in the physical properties of materials under various conditions, foremost among which is temperature. These phenomena are reversible, and their effects can be eliminated by suitable design, or systematic compensation. The other class gives rise to random errors and includes such things as lost motion, undesirable friction, and instability. These are within the province of detail design and will be discussed in the paragraph devoted to it.

Temperature. The most common effect of temperature is to cause materials to change in length, which gives little trouble in average laboratory and industrial apparatus as long as the designer has a free choice of material, but difficulties arise for example when metals have to meet various requirements at once, then if expansion effects cannot be overcome by symmetrical design, compensation with a composite structure must be tried, using special nickel steels such as invar, if necessary.

Elasticity also changes with temperature, and, for example, the effects of this are such that a steel tuning fork vibrates more slowly with rising temperature, whilst an alarm clock with a phosphor-bronze hairspring tends to lose time, and an aneroid barometer to read low. These tendencies can be greatly reduced by the use of special metals; elinvar could be used with advantage for both the tuning fork and the clock balance spring. The barometer can be corrected by the application of a piece of bimetal either to alter the apparent zero, or to adjust the "rate" of the multiplying mechanism.

Temperature errors are particularly serious in electrical instruments, and frequently they can be avoided only by null methods. The chief trouble arises from the change of resistance of good conductors; for pure metals it is about 0.4% per 1° C. Often the effect can be swamped by adding a resistance made of manganin or constantan, but the circuit will not always permit this, then one has recourse to a composition resistance with a negative coefficient, or to shunting the magnet gap of the instrument with thermo-magnetic alloy. These materials have such a low Curie point that their permeability varies considerably over the useful range of ambient temperature. Thus a rise in temperature causes less flux to be carried by the shunt, and more to be forced across the gap to an extent depending on the proportions of the components. These alloys usually contain nickel and iron, or nickel and copper as the main constituents. The problem of compensation is more complex when the circuit contains such items as composition resistors and metal rectifiers whose characteristics do not follow a straight line law.

Condensers also show temperature effects. Capacity variations are due to change in the constant of the dielectric, but leakage currents also vary, electrolytic condensers showing this effect to a marked extent. It should be remembered that all insulators tend to be less efficient as temperatures rise, and that leakage currents will increase.

Other properties showing temperature changes are viscosity and surface tension. The former may affect the performance of a fluid damping device if it depends on viscosity effects, and will certainly cause lubricating oils to thicken at low temperatures. This problem can be acute in aircraft instruments which have to work at low temperatures, but synthetic lubricants such as Silicone oils with a comparatively small viscosity coefficient are now becoming available.

Humidity. Moisture can cause general deterioration in the performance of an instrument through corrosion of metal parts, by causing swelling of components of other materials, and by increasing the electrical leakage over insulators, but it does not generally affect the accuracy directly except in recording instruments. Paper changes its dimensions with varying humidity, and although precautions can be taken to minimise the effects of this in the design of an instrument, chart papers should be selected by test to see that they are not too sensitive to moisture. Consideration has also to be given to the process used to print them.

Acceleration. This can usually be neglected in designing stationary apparatus, but has to be considered most carefully if measuring instruments have to function on a moving vehicle or a ship, or in an aircraft. The effects can be eliminated by balancing each moving component, if possible. Should this not be practicable then linked components must be treated as a group, when the nature and quality of the linkages may be important, especially if the acceleration is rapidly alternating in the form of a vibration.

Constructional Details

The design of scientific instruments can follow conventional mechanical principles, but constructions satisfactory in a machine may not be good enough in a precise measuring instrument unless it be made at prohibitive cost by craftsmen. When geometric principles of design can be applied they overcome most of this difficulty, and although their advantages have been appreciated by some designers for many years, they could be exploited to a much greater extent even to-day, to the benefit of both makers and users, for the intelligent application of these principles eliminates many sources of random errors, and greatly facilitates assembly and adjustment.

A geometric design may be defined as one which allows a member to have only those degrees of freedom which it is required to have, meaning that the number of constraints plus the degrees of freedom,

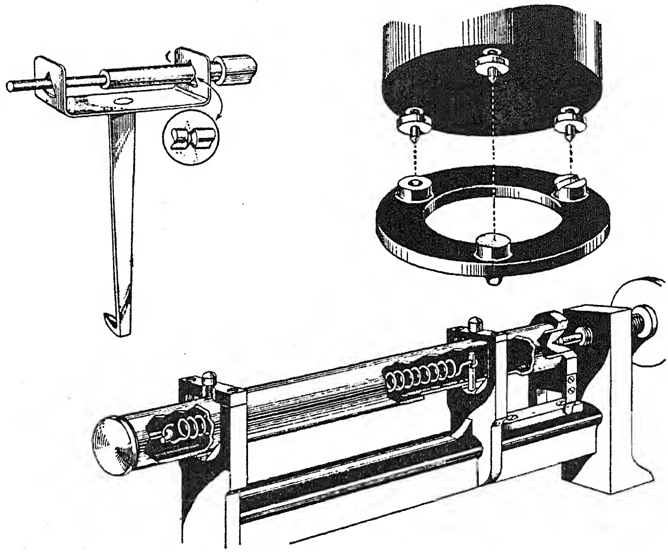

Fig. XXIV. 1. Geometric constructions showing pen support for a recording instrument, a base for a galvanometer and a slide for a travelling microscope.

shall total six. Moreover this result can be achieved by using simple geometric forms capable of production by easy machining operations as illustrated by the examples in Fig. XXIV. 1. In practice the most smooth and precise motions can be provided with economy in an instrument convenient in use, for this construction gives very definite locations for demountable components. In the general way, pressure at points of constraint may be high. This does not matter in a rotational or sliding adjustment or slow motion, but it is not suitable for more continuous or rapid movements. Fortunately it is possible to design ball bearings on geometric principles to handle continuous rotation, but such may not be adaptable to high speeds. Furthermore, the members of a geometric construction have to be held together. Gravity can provide the necessary force in some designs, but in others springs of various forms are used, and it will be obvious that these will become excessively strong if parts are to be held together in different attitudes, and under vibration. In these circumstances it is better to abandon the principle altogether, which accounts for its general absence from aircraft instruments. Whatever system of design is adopted many common elements will be used, and these will now be discussed in detail.

General Construction. At one time the bases and frameworks of instruments were either made from castings, or fabricated from sheet, strip, or tubular forms of a few raw materials, but modern techniques offer many alternatives both in methods of construction and materials. Some of these are particularly suited to quantity production, and have rendered a great service to industry by increasing the availability of instruments, but care is needed in their application to instruments of the highest precision.

For example, pressure or gravity die-castings can be made in alloys of tin, zinc and aluminium, to mention the commonest. Tin base alloys can be very precise, and are stable but soft. Zinc alloys can be cast in the most elaborate forms, but they tend to grow to an extent depending on the purity of the zinc. Aluminium die-castings are more stable, particularly if internal stresses are relieved by heat-treatment. This is especially necessary when dealing with a gravity casting, or a forging when metal has been machined off, otherwise creep may follow over a long period. In fact it is not generally realised how long it takes for stresses to settle down in deformed materials kept at normal temperatures. Therefore adjustment by bending is to be avoided, and pressed components should be stress-relieved, and this also applies to parts turned from cold-worked metals like free-cutting mild steel, and cold-drawn brass bar, if much has been removed.

Insulation. A wide variety of insulating materials is now on the market, including plastic moulding compositions with various fillings, synthetic resin sheets having paper, fabric, or glass fibre bases, and ceramics. Large components are usually made as mouldings, or machined from synthetic resin sheet, but they should not be included as part of a mechanical structure. Their dimensions change rather

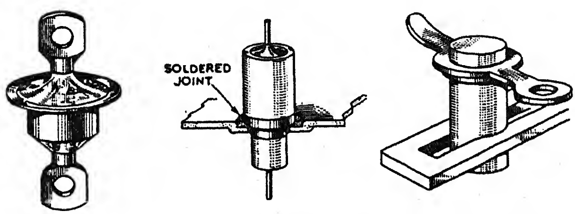

Fig. XXIV. 2. Ceramic insulators for current leads into a slide container and as a mechanical support.

indefinitely with temperature, and over a period there is some shrinkage. When one requires mechanical rigidity of an insulated member it is better to use washers and bushes of mica or thin resin sheet, or a ceramic construction. Fig. XXIV. 2 shows two types of seal,

either of glass or silvered ceramic, which can be soldered into place, and a third version in which the great strength of ceramics in compression is used in building up a force-fitted construction. That this form of ceramic is expensive when small numbers are needed does not prevent their use in individual instruments or experimental models for they can be machined from South Afiican Wonderstone, or Pyrophilite, which after heating has similar properties to fired ceramics.

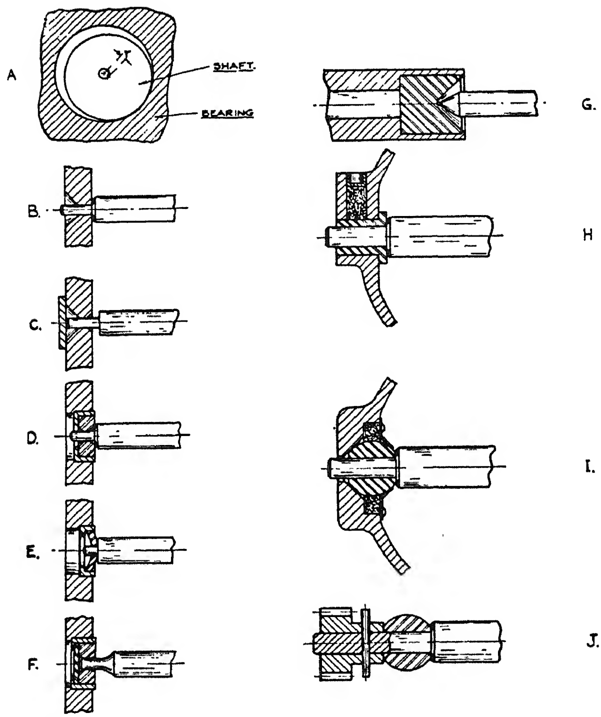

Fig. XXIV. 3. Instrument bearings for rotating members.

Journal Bearings. (See Fig. XXIV. 3.) Bearings for rotating members play an important part in instruments, and can take many forms. Fundamentally, there must be clearance in a bearing for it to be free to turn, but this results in some uncertainty as to its centre of rotation. This is shown at A, Fig. XXIV. 3, the centre of the shaft being able to take up a position anywhere within the small circle with radius equal to the radial clearance between the shaft and bearing. This factor must enter into the choice of a bearing.

B represents the simplest type, a shouldered spindle running in a hole. This is not capable of carrying much end-thrust, and clearance has to be allowed to accommodate mis-alignment, so this form is used mainly in simple mechanisms such as pressure gauge movements, and clocks, although it can be altered by the addition of a thrust pad to handle more end-thrust, as indicated at C. Since there is no difficulty in making the pivots of hard steel, the wearing properties of this form of bearing are limited by the hardness of the plate, and so can be improved by inserting hard bushes of phosphor-bronze, or even tungsten carbide, or best of all jewelled bearings of synthetic sapphire. Such bearings are made commercially with great precision, and high finish, so that with a hard steel pivot, friction and uncertainty of location are at a minimum. The simplest form is shown at D. This is equivalent to B, end-thrust being borne by a shoulder running on a flat surface. Friction at this point can be lessened by the bombé form (E), and reduced to a minimum by the design shown at F. Jewelled bearings are commonly used in aircraft instruments, and to a great extent in small timepieces, the last form mentioned being specially applicable to the balance staff. It will be noted that these sketches show the jewel mounted in a bush, or "chaton". This lessens the risk of cracking the stone when fitting it to the plate, but if special jewelling machines are used it is possible to mount them straight into the plate. It will be noted, also, that the bores of the stones are not parallel, but "olived," and this allows small clearances without serious risk of binding due to mis-alignments.

Although the form of bearing, shown at F, has relatively little friction, its components would be too small if reduced to the proportions sufficient to carry the moving system of an electrical instrument, therefore all but the largest use the form seen at G that is a conical pivot in a cup jewel. Whilst this will obviously perform best when the axis of rotation is vertical, it does in fact work quite well in any attitude. Clearly any end-play between the parts of such bearings means that the centre of rotation is not well defined, but any uncertainty is negligible compared with the length of the pointer. Opinions differ as to the best angle for both pivot and jewel, but a pivot with an angle of 65—70°, in a 90° recess, is common practice, the radius at the tip of the pivot being less than 0.001 in., and that in the jewel about three times this figure. The figure shows the stone mounted rigidly in the jewel-screw, although sometimes it is a sliding fit and held up by a spring to absorb shocks.

Even with lubrication, jewelled bearings do not perform well at high speeds of continuous rotation. Local bearing pressures can be high, and the jewel itself is a thermal insulator, so the pivot soon wears. Bushes of phosphor-bronze can be good, and so can steel ones, but they too require adequate lubrication. This can be provided

by using porous phosphor-bronze, and a very wide variety of sizes is now commercially available, and practical applications are suggested at H and I, Fig. XXIV. 3. In the first the shaft is running in a parallel bush, force-fitted into a cast housing with an oil reservoir having a piece of felt in it. I shows a bearing with self-aligning features, and in this case the reservoir takes the form of a ring. Certain precautions have to be taken in the fitting of these bearings, and in their impregnation with oil, but this information is furnished readily by the makers.

Sometimes a design requires that end-play shall be small, when, for example, a shaft is running in a frame such as a motor. This can be adjusted by shims, but a better arrangement is to control it at one end as suggested at J, leaving the shaft to slide in a parallel bearing at the other end. This scheme is valuable when the shaft and frame are of different metals, and is even more useful when ball bearings are employed.

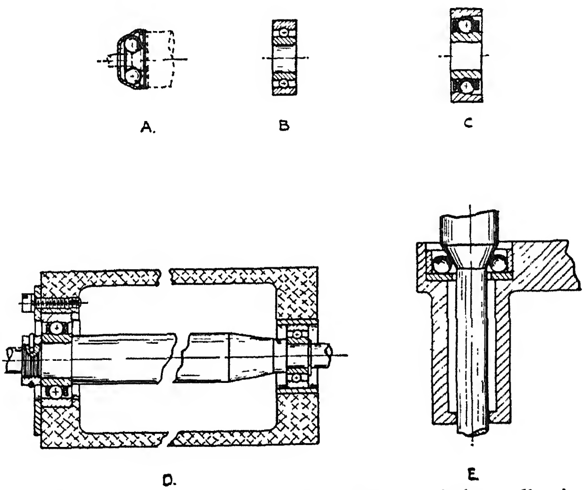

Fig. XXIV. 4. Forms of ball bearings, and their application.

Ball bearings are now available in such small sizes that they can compete with the larger jewel bearings. They may take the form shown at A, Fig. XXIV. 4, and it will be noted that the spindle is shaped to constitute the inner race. These little bearings are not yet in general use, and the types which usually interest the instrument maker are shown at B and C. The first is supplied as a complete unit for spindles down to $\frac{1}{8}$ in. diameter. That shown at C is called a magneto bearing, it is assembled in the mechanism so that clearances

and end-play can be made very small. Complete bearings, like that at B, are fitted so that they are either tight on the shaft, in the housing, or both. This means that force is necessary to fit or remove them, and the design must allow for this force to be applied directly to the component concerned, and not through the balls. These bearings have very little end-play themselves, so cannot accommodate endwise movement without becoming stiff. The manner in which these points can be taken care of in an actual design is illustrated at D, representing a sound layout for a steel shaft running in bearings in an aluminium alloy casting. The left hand bearing is a force fit on the shaft, and further clamped by a locked nut. The outer race is a sliding fit in its housing in which it is clamped by a plate, so the shaft is located at that end. The bearing at the other end is also a tight fit on the shaft, but its position is not critical, so a clip ring is fitted for safety to prevent its coming right off. The outer race is a sliding fit in its housing to take up accumulated errors in components, and the effects of temperature changes, but the possible movements would gradually enlarge the housing, when the bearing would become completely loose, so a steel lining is force-fitted and machined in place.

Ball bearings of this kind are not really suitable for such things as gyroscope wheels, which must be accurately located while revolving at high speeds. The magneto bearing does better, but it is more usual to form the inner race as part of a short stout spindle, and to use rather special contours. These have to be made with the utmost precision from selected metal, and loaded with balls having what is known as a "satin" finish. Reference has been made to the use of ball bearings in geometric designs. An example of such is the application to a loaded vertical spindle drawn at E, Fig. XXIV.4. The weight is carried by the balls running in a race assembled from simple parts, and obviously has no uncertainty of location, being steadied by the plain, unloaded bearing below.

Springs are employed in instruments either to provide restraining forces to hold elements together, or to serve as a metering element, and for either the spring can be in the form of a helix, spiral, or leaf. A spring for the first application can be made to wide performance tolerances, but the second demands at least stability, even if adjustments in the instrument allow some latitude in actual strength. The most common materials from which springs can be made are listed in Table I, with design data. Steel, beryllium-copper, and phosphor-bronze have the best elastic properties, but other metals have different virtues, and so other uses. Cadmium copper has a low ohmic resistance and makes good springs for small electrical instruments ; elinvar provides springs for horological escapements which compensate for temperature changes in the balance wheel, whilst stainless steel resists corrosive atmospheres.

TABLE I.

	BENDING			TORSION		
	Module of Elasticity and Tension. lb./sq. in.	Max. Stress in calibrated Hairsprings lb./sq. in.	Max. Stress in Leaf Springs. lb./sq. in.	Module of Elasticity and Torsion. lb./sq. in.	Max. Stress in Helical Springs. lb./sq. in.	Specific Resistance Microhms per cm^3
Steel 1% C.	30×10^6	4×10^4	10×10^4	11×10^6	8×10^4	—
Stainless Steel (18/8)	30×10^6	1×10^4	4×10^4	—	—	—
Phosphor Bronze	15×10^6	1×10^4	4×10^4	6×10^6	4×10^4	5
Beryllium Copper	18×10^6	2×10^4	8×10^4	7×10^6	6×10^4	7
Cadmium Copper	11×10^6	0.5×10^4	—	5×10^6	—	2
Elinvar	20×10^6	1.5×10^4	—	—	—	75

Carbon steel is often used in the cold drawn state as piano wire, and excellent performance as a metering spring results from treatment at 300° C. Leaf springs can be cropped from spring strip, or if of more complicated shape punched from hard or soft strip. When the first is used care is necessary to see that the tool is in good condition, or cracks will be started at the edges and spoil the result. The second is more suitable when the spring has to be bent, for it can be hardened and tempered after.

Phosphor-bronze can be made into all types of springs, and any stress resulting from bending can be relieved, and the spring "set" by treatment at about 300° C, without seriously spoiling the elastic properties. Beryllium copper can be handled and formed in the soft condition, for it is a precipitation hardening alloy, and heat-treatment develops excellent elastic properties without internal stress. These are seen to advantage when this alloy is used for hairsprings in instruments with pointer deflections of 270°, or more. It is also resistant to fatigue and the effects of vibration, so it is a unique spring material. The strength of leaf, and helical springs, whether the latter are for use in tension or compression can be measured by direct loading, and with the right apparatus spiral springs can be tested in a similar way, or compared with one of known properties, but the best results are obtained by calculation from the observed time of oscillation of a known inertia bar under the control of the spring. Certain precautions have to be exercised in the preparation of metering springs. Helical tension springs should have the end loops brought out in even curves, and shaped to give a definite location, compression springs must have the ends ground square with

the axis. Undue concentration of stress at the clamping point of leaf springs is avoided if the sharp edges are taken off the clamps, and hairsprings must be clamped, pinned or soldered at both ends so that the effective length is definite, and they should be mounted without "setting" if risk of creep is to be avoided.

Damping

The time taken to reach a steady reading is often important not only with indicating instruments, but also in the balance detector in null systems, and if fluctuating quantities are to be measured the whole design may start from this point. The moment of inertia of moving parts, and the degree of damping must be calculated to give the necessary response, and in deciding on the method of damping to be applied in any one case, the principle of negative feed-back should not be overlooked, neither must the effect of high-frequency variations possibly resonating with part of a mechanism whilst the whole has a longer, and well damped period. This effect is sometimes noted in rectifier instruments for measuring alternating currents when used on some unusual frequency.

Scales

Since the final purpose of an instrument is to give a reading of some kind, the means by which this is done is important, and one on which the instrument may be judged. The pointer and scale arrangement is the most common, and this may have to be bold to be read at a glance, like a clock or speedometer, or it may be finely divided for careful observation as on a standard voltmeter, whilst something between the two is called for on power station instruments, and industrial pyrometers.

A suitable scale for precision readings is suggested in Fig. XXIV. 5, noteworthy features being that the subdivisions are all alike in

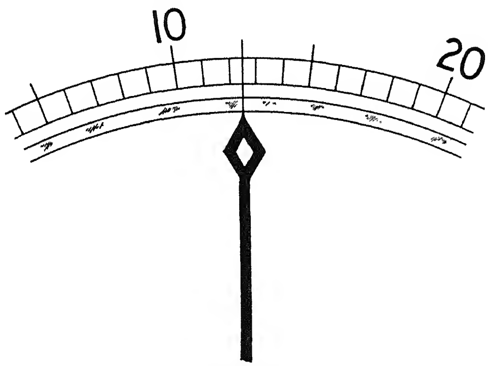

Fig. XXIV. 5. Instrument scale and pointer design.

thickness, and the same as the pointer, that the length of these subdivisions is about the same as the distance between them to help interpolation, and that there is a mirror enabling parallax errors to be avoided. The legibility from a distance can be improved by enlarging the flag on the pointer and the figures, without sacrifice of precision, but the same attention to proportions is not necessary on bold types of scale which give opportunities for an artistic approach. Measuring scales can, with advantage, have proportions like those in Fig. XXIV. 5 whatever their size, and however they are read, whether with an index or pointer, or with a graticule in an optical system. This applies also to projected scales, which appear so attractive when lighting is poor, and have the added advantage that parallax is absent.

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SOME DEFINITIONS AND DATA

Mechanics

1 *Dyne* is the force required to impart to a mass of 1 gram an acceleration of 1 centimetre/second/second.

1 *Erg* is the work done when a force of 1 dyne moves through 1 centimetre in the direction of the force.

The *dyne* and the *erg* correspond respectively to the *poundal* and the *foot-poundal* in the foot-pound-second system.

Power is the rate of doing work.

1 gram-weight	=	981 dynes (approx.)
1 pound-weight	=	32.2 poundals (approx.)
1 poundal	=	13,825 dynes.
1 centimetre-gram	=	981 ergs.
1 foot-pound	=	13.56×10^6 ergs.
1 horse-power	=	7.46×10^9 ergs/second.
	=	550 foot-pounds/second.
	=	33,000 foot-pounds/minute.
	=	746 watts.
	=	178,120 calories/second.

Mechanical Equivalent of Heat

$$W = J.H.$$

where H is the heat equivalent of energy W and J = Joule's constant

$=4.18 \times 10^7$ ergs/calorie.

$=4.18$ joules/calorie.

Thermometry

$t°C = (\frac{9}{5}t + 32)°\ F$ $\qquad$ $t°K$ (or $t°$Abs) $= t°C + 273°$

$t°F = \frac{5}{9}(t - 32)°\ C$ $\qquad$ or $\qquad$ $\frac{F-32}{9} = \frac{C}{5} = \frac{R}{4}$

Electrical

Specific Resistance or resistivity is the resistance between opposite faces of a cube each side of which has unit length, at a given temperature.

Resistance $R = \frac{\sigma L}{a}$ where L = length of conductor,

a = area of cross section,

and σ = specific resistance.

Capacitance of a conductor is the ratio of the charge on it to its potential when all neighbouring conductors are at zero potential (practical unit: farad).

Inductance is that property of a circuit whereby a change in the magnetic flux linked with the circuit causes an E.M.F. to be induced in it (practical unit: henry).

Atomic Physics

Equivalence of Mass and Energy

$E = m c^2$, where c is the velocity of light.

Energy of a quantum

$E = h \nu$, where ν is the frequency

and h = Planck's constant = 6.62×10^{-27} erg seconds.

Mass of a moving body

$m = m_o / \sqrt{(1 - v^2)}$

m_o = mass of the body at rest

v = velocity of body ÷ velocity of light

Wavelengths and Frequencies of Different Kinds of Radiation (approximations)

Nature of Radiation	Wavelength in cm	Frequency
Electric waves ..	From 10^{6} to 10^{-2}	From 3×10^{4} to 3×10^{12}
Infra-red waves ..	From 10^{-1} to 10^{-4}	From 3×10^{11} to 3×10^{14}
Visible light ..	From 10^{-4} to 10^{-5}	From 3×10^{14} to 3×10^{15}
Ultra-violet rays ..	From 10^{-5} to 10^{-7}	From 3×10^{15} to 3×10^{17}
X-rays	From 10^{-6} to 10^{-9}	From 3×10^{16} to 3×10^{19}
γ-rays	From 10^{-8} to 10^{-11}	From 3×10^{18} to 3×10^{21}

Optics

Some typical wavelengths in the visible spectrum

It is usual to express wavelengths in Ångstrom units (Å).

1 Å = 10^{-8} centimetre

Red .. .. 6000-7500 Å

Yellow (sodium) 5893 Å

Violet .. .. 4000-4300 Å

Other units for expressing wavelengths are the micron and the millimicron

1 micron (μ) = 10^{-4} centimetre

1 millimicron ($m\mu$) = 10^{-7} centimetre

Velocity of light = $(2.99796 \pm .00004) \times 10^{10}$ centimetres per second (in vacuo) or more commonly given as 300,000 kilometres/second or 186,000 miles/second.

Sound

Velocity of sound in air = approx. 365 yards/second, or, say, 1 mile in 5 seconds.

Range of human audible-frequency, 30-15,000 vibrations per second.

Middle A 213·3, Middle C 256 vibrations per second (scientific scale).

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